2007 ASHRAE® HANDBOOK

Heating, Ventilating, and Air-Conditioning APPLICATIONS

Inch-Pound Edition

American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

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DEDICATED TO THE ADVANCEMENT OF

THE PROFESSION AND ITS ALLIED INDUSTRIES

Volunteer members of ASHRAE Technical Committees and others compiled the information in this handbook, and it is generally reviewed and updated every four years. Comments, criticisms, and suggestions regarding the subject matter are invited. Any errors or omissions in the data should be brought to the attention of the Editor. Additions and corrections to Handbook volumes in print will be published in the Handbook published the year following their verification and, as soon as verified, on the ASHRAE Internet Web site.

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The American Society of Heating, Refrigerating and Air-Conditioning Engineers is the world's foremost technical society in the fields of heating, ventilation, air conditioning, and refrigeration. Its members worldwide are individuals who share ideas, identify needs, support research, and write the industry's standards for testing and practice. The result is that engineers are better able to keep indoor environments safe and productive while protecting and preserving the outdoors for generations to come.

One of the ways that ASHRAE supports its members' and industry's need for information is through ASHRAE Research. Thousands of individuals and companies support ASHRAE Research annually, enabling ASHRAE to report new data about material properties and building physics and to promote the application of innovative technologies.

Chapters in the ASHRAE Handbook are updated through the experience of members of ASHRAE Technical Committees and through results of ASHRAE Research reported at ASHRAE meetings and published in ASHRAE special publications and in *ASHRAE Transactions*.

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Preface

The 2007 *ASHRAE Handbook—HVAC Applications* covers a broad range of facilities and topics, and is written to help engineers design and use equipment and systems described in other Handbook volumes. ASHRAE Technical Committees have revised nearly every chapter for current requirements and techniques. An accompanying CD-ROM contains all the volume's chapters in both I-P and SI units.

This edition includes *three* new chapters, described as follows:

- Chapter 56, Room Air Distribution, intended to help HVAC designers apply air distribution systems to occupied spaces, has information on air distribution strategies, and tools and guidelines for applications and system design.
- Chapter 57, Integrated Building Design, describes this process and the activities that support collaboration among design participants, and identifies major milestones for project delivery.
- Chapter 58, Chemical, Biological, Radiological, and Explosive Incidents, describes these types of events, their effects on buildings, occupants, and equipment, and offers general guidelines on how to deal with them.

Some of the revisions and additions to the remainder of the volume are as follows:

- Chapter 6, Educational Facilities, rewritten and expanded, now has comprehensive design criteria for preschools through universities, plus detailed content on applying dedicated outside air systems (DOAS), displacement ventilation, and other strategies.
- Chapter 7, Health Care Facilities, updated throughout for current guidelines and standards, has new content on pharmacies, including sterile compounding areas.
- Chapter 8, Justice Facilities, has new sections on jails, prisons, family courts, courthouses, and forensic labs.
- Chapter 9, Automobiles and Mass Transit (formerly entitled Surface Transportation), has been extensively revised, with updates on refrigerant phaseouts and new technology, plus detailed content on system components, including many new illustrations.
- Chapter 16, Clean Spaces, has new content on differential pressurization control between rooms, air locks, aseptic pharmaceutical processing areas, and improving the sustainability of these facilities.
- Chapter 17, Data Processing and Electronic Office Areas, has been completely rewritten to reflect current technology.
- Chapter 21, Museums, Galleries, Archives, and Libraries, retitled, now covers galleries and has a major new table listing relevant gaseous pollutants, their sources, and at-risk materials.
- Chapter 31, Kitchen Ventilation, has been updated extensively with recent research results on hood capture and containment, makeup air configurations, and grease particle capture, plus new text on residential applications.
- Chapter 32, Geothermal Energy, has new sections on pumps and piping for ground-coupled heat pumps, standing-column groundwater heat pump systems, plus a new residential vertical design example.
- Chapter 34, Thermal Storage, has new sections on sensible energy change storage, chilled-water and low-temperature fluid applications, hydronic design for open systems, and using building thermal mass.
- Chapter 35, Energy Use and Management, reorganized to facilitate its use in program planning, has much rewritten content, especially the section on analyzing energy data.
- Chapter 36, Owning and Operating Costs, has been extensively updated, with new data on equipment service life, energy costs, and other factors.
- Chapter 38, Operation and Maintenance Management, revised throughout, has a new section on detecting and diagnosing equipment faults, plus new tables on equipment fault frequencies.
- Chapter 44, Building Air Intake and Exhaust Design, has revisions to dilution calculations, the parameters involved, and methods surrounding their use.
- Chapter 48, Water Treatment, has new information on research results for nonchemical treatment methods.
- Chapter 45, Control of Gaseous Indoor Air Contaminants, has new information on air cleaner configurations, and filter housing and adsorber module integrity.
- Chapter 46, Design and Application of Controls, has been completely reorganized, with many new or modified diagrams and revised sections.
- Chapter 47, Sound and Vibration Control, has been substantially rewritten, including many procedures and examples.
- Chapter 49, Service Water Heating, updated with added discussion of equipment sizing methods, also has new sections on distribution piping heat loss, hot-water delivery delays, and computing system energy use.

This volume is published, both as a bound print volume and in electronic format on a CD-ROM, in two editions: one using inch-pound (I-P) units of measurement, the other using the International System of Units (SI).

Corrections to the 2004, 2005, and 2006 Handbook volumes can be found on the ASHRAE Web site at http://www.ashrae.org and in the Additions and Corrections section of this volume. Corrections for this volume will be listed in subsequent volumes and on the ASHRAE Web site.

Reader comments are enthusiastically invited. To suggest improvements for a chapter, **please comment using the form on the ASHRAE Web site** or write to Handbook Editor, ASHRAE, 1791 Tullie Circle, Atlanta, GA 30329, or fax 678-539-2187, or e-mail mowen @ashrae.org.

Mark S. Owen
Editor

The four-volume ASHRAE Handbook is a reference for engineers working in HVAC&R and for professionals in allied fields. The print edition is revised on a four-year cycle, with one volume published each year. Tables of contents for the four most recent volumes appear on these pages, and a composite index is at the end of this volume. In addition to the CD-ROM accompanying this book, ASHRAE publishes a HandbookCD+ containing all four volumes plus supplemental material and features. The Society also produces educational materials, standards, design guides, databases, and many other useful publications. See the online bookstore of the ASHRAE Web site (www.ashrae.org) for information on these publications.

2007 HVAC APPLICATIONS

2006 REFRIGERATION

2005 FUNDAMENTALS

2004 HVAC SYSTEMS AND EQUIPMENT

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2007 *ASHRAE Handbook—HVAC Applications* CD-ROM

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CHAPTER 2

RETAIL FACILITIES

THIS chapter covers design and application of air-conditioning and heating systems for various retail merchandising facilities. Load calculations, systems, and equipment are covered elsewhere in the Handbook series.

GENERAL CRITERIA

To apply equipment properly, the construction of the space to be conditioned, its use and occupancy, the time of day in which greatest occupancy occurs, physical building characteristics, and lighting layout must be known.

The following must also be considered:

- Electric power—size of service
- Heating—availability of steam, hot water, gas, oil, or electricity
- Cooling—availability of chilled water, well water, city water, and water conservation equipment
- Internal heat gains
- Rigging and delivery of equipment
- Structural considerations
- Obstructions
- Ventilation—opening through roof or wall for outside air duct, number of doors to sales area, and exposures
- Orientation of store
- Code requirements
- Utility rates and regulations
- Building standards

Specific design requirements, such as the increase in outside air required for exhaust where lunch counters exist, must be considered. The requirements of ASHRAE ventilation standards must be followed. Heavy smoking and objectionable odors may necessitate special filtering in conjunction with outside air intake and exhaust. Load calculations should be made using the procedure outlined in Chapter 30 of the 2001 *ASHRAE Handbook—Fundamentals.*

Almost all localities have some form of energy code in effect that establishes strict requirements for insulation, equipment efficiencies, system designs, etc., and places strict limits on fenestration and lighting. The requirements of ASHRAE *Standard* 90 should be met as a minimum guideline for retail facilities.

HVAC system selection and design for retail facilities are normally determined by economics. First cost is usually the determining factor for small stores; for large retail facilities, operating and maintenance costs are also considered. Generally, decisions about mechanical systems for retail facilities are based on a cash flow analysis rather than on a full life-cycle analysis.

SMALL STORES

Large glass areas found at the front of many small stores may cause high peak solar heat gain unless they have northern exposures. High heat loss may be experienced on cold, cloudy days. The HVAC system for this portion of the small store should be designed to offset the greater cooling and heating requirements. Entrance vestibules and heaters may be needed in cold climates.

Many new small stores are part of a shopping center. Although exterior loads will differ between stores, internal loads will be similar; proper design is important.

Design Considerations

System Design. Single-zone unitary rooftop equipment is common in store air conditioning. Using multiple units to condition the store involves less ductwork and can maintain comfort in the event of partial equipment failure. Prefabricated and matching curbs simplify installation and ensure compatibility with roof materials.

Heat pumps, offered as packaged equipment, are readily adaptable to small-store applications and have a low first cost. Winter design conditions, utility rates, and operating cost should be compared to those for conventional heating systems before this type of equipment is chosen.

Water-cooled unitary equipment is available for small-store air conditioning, but many U.S. communities restrict the use of city water and groundwater for condensing purposes and require installation of a cooling tower. Water-cooled equipment generally operates efficiently and economically.

Retail facilities often have a high sensible heat gain relative to the total heat gain. Unitary HVAC equipment should be designed and selected to provide the necessary sensible heat removal.

Air Distribution. External static pressures available in small-store air-conditioning units are limited, and ducts should be designed to keep duct resistances low. Duct velocities should not exceed 1200 fpm and pressure drop should not exceed 0.10 in. of water per 100 ft. Average air quantities range from 350 to 450 cfm per ton of cooling in accordance with the calculated internal sensible heat load.

Attention should be paid to suspended obstacles, such as lights and displays, that interfere with proper air distribution.

The duct system should contain enough dampers for air balancing. Dampers should be installed in the return and outside air duct for proper outside air/return air balance. Volume dampers should be installed in takeoffs from the main supply duct to balance air to the branch ducts.

Control. Controls for small stores should be kept as simple as possible while still able to perform required functions. Unitary equipment is typically available with manufacturer-supplied controls for easy installation and operation.

Automatic dampers should be placed in the outside air intake to prevent outside air from entering when the fan is turned off.

Heating controls vary with the nature of the heating medium. Duct heaters are generally furnished with manufacturer-installed safety controls. Steam or hot-water heating coils require a motorized valve for heating control.

Time clock control can limit unnecessary HVAC operation. Unoccupied reset controls should be provided in conjunction with timed control.

Maintenance. To protect the initial investment and ensure maximum efficiency, maintenance of air-conditioning units in small

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The preparation of this chapter is assigned to TC 9.8, Large Building Air-Conditioning Applications.

stores should be contracted out to a reliable service company on a yearly basis. The contract should clearly specify responsibility for filter replacements, lubrication, belts, coil cleaning, adjustment of controls, compressor maintenance, replacement of refrigerant, pump repairs, electrical maintenance, winterizing, system start-up, and extra labor required for repairs.

Improving Operating Cost. Outside air economizers can reduce the operating cost of cooling in most climates. They are generally available as factory options or accessories with roof-mounted units. Increased exterior insulation generally reduces operating energy requirements and may in some cases allow the size of installed equipment to be reduced. Many codes now include minimum requirements for insulation and fenestration materials.

DISCOUNT, BIG-BOX, AND SUPERCENTER STORES

Large warehouse or big-box stores attract customers with discount prices when large quantities are purchased. These stores typically have high-bay fixture displays and usually store merchandise in the sales area. They feature a wide range of merchandise and may include such diverse areas as a lunch counter, an auto service area, a supermarket, a pharmacy, and a garden shop. Some stores sell pets, including fish and birds. This variety of merchandise must be considered in designing air conditioning. The design and application suggestions for small stores also apply to discount stores.

Another type of big-box facility provides both dry good and grocery areas. The grocery area is typically treated as a traditional stand-alone grocery (see the section on Supermarkets). Conditioning outside air for the dry goods areas must be considered to limit the introduction of excess moisture that will migrate to the freezer aisles.

Hardware, lumber, furniture, etc., is also sold in big-box facilities. A particular concern in this type of facility is ventilation for material-handling equipment, such as forklift trucks.

In addition, areas such as stockrooms, rest rooms, offices, and special storage rooms for perishable merchandise may require air conditioning or refrigeration.

Load Determination

Operating economics and the spaces served often dictate inside design conditions. Some stores may base summer load calculations on a higher inside temperature (e.g., 80°F db) but then set the thermostats to control at 72 to 75°F db. This reduces the installed equipment size while providing the desired inside temperature most of the time.

Special rooms for storage of perishable goods are usually designed with separate unitary air conditioners.

The heat gain from lighting will not be uniform throughout the entire area. For example, jewelry and other specialty displays typically have lighting heat gains of 6 to 8 W per square foot of floor area, whereas the typical sales area has an average value of 2 to 4 W/ft². For stockrooms and receiving, marking, toilet, and rest room areas, a value of 2 W/ft² may be used. When available, actual lighting layouts rather than average values should be used for load computation.

The store owner usually determines the population density for a store based on its location, size, and past experience.

Food preparation and service areas in discount and outlet stores range from small lunch counters with heat-producing equipment (ranges, griddles, ovens, coffee urns, toasters) in the conditioned space to large deluxe installations with kitchens separate from the conditioned space. Chapter 31 has specific information on HVAC systems for kitchen and eating spaces.

Data on the heat released by special merchandising equipment, such as amusement rides for children or equipment used for preparing speciality food items (e.g., popcorn, pizza, frankfurters,

hamburgers, doughnuts, roasted chickens, cooked nuts, etc.), should be obtained from the equipment manufacturers.

Ventilation and outside air must be provided as required in ASHRAE *Standard* 62 and local codes.

Design Considerations

Heat released by installed lighting is usually sufficient to offset the design roof heat loss. Therefore, interior areas of these stores need cooling during business hours throughout the year. Perimeter areas, especially the storefront and entrance areas, may have highly variable heating and cooling requirements. Proper zone control and HVAC design are essential. The location of checkout lanes in this area makes proper environmental control even more important.

System Design. The important factors in selecting discount and outlet store air-conditioning systems are (1) installation costs, (2) floor space required for equipment, (3) maintenance requirements and equipment reliability, and (4) simplicity of control. Roof-mounted units are most commonly used.

Air Distribution. The air supply for large sales areas should generally be designed to satisfy the primary cooling requirement. For perimeter areas, the variable heating and cooling requirements must be considered.

Because these stores require high, clear areas for display and restocking, air is generally distributed from heights of 14 ft and greater. Air distribution at these heights requires high velocities in the heating season to overcome the buoyancy of hot air. The discharge air velocity creates turbulence in the space and induces airflow from the ceiling area to promote complete mixing of the air.

During the cooling season the designer can take advantage of stratification to reduce equipment load. By introducing air near customers at low velocity, the air will stratify during the cooling season. With this method of air distribution, the set-point temperature can be maintained in the occupant zone and the temperature in the upper space can be allowed to rise. However, this strategy requires equipment to destratify the air during the heating season. Space-mounted fans, and radiant heating at the perimeter, entrance, and sales areas may be required.

Control. Because the controls are usually operated by personnel who have little knowledge of air conditioning, systems should be simple, dependable, and fully automatic, as simple to operate as a residential system. Most unitary equipment has automatic electronic controls for ease of operation.

Maintenance. Most stores do not employ trained maintenance personnel; they rely instead on service contracts with either the installer or a local service company. For suggestions on lowering operating costs, see the section on Small Stores.

SUPERMARKETS

Load Determination

Heating and cooling loads should be calculated using the methods outlined in Chapter 30 of the 2001 *ASHRAE Handbook—Fundamentals*. Data for calculating loads caused by people, lights, motors, and heat-producing equipment should be obtained from the store owner or manager or from the equipment manufacturer. In supermarkets, space conditioning is required both for human comfort and for proper operation of refrigerated display cases. The air-conditioning unit should introduce a minimum quantity of outside air, either the volume required for ventilation based on ASHRAE *Standard* 62 or the volume required to maintain slightly positive pressure in the space, whichever is larger.

Many supermarkets are units of a large chain owned or operated by a single company. The standardized construction, layout, and equipment used in designing many similar stores simplify load calculations.
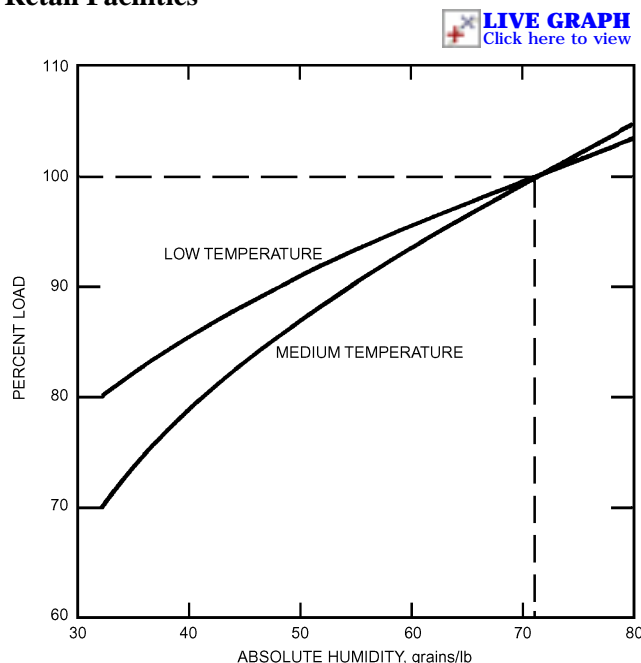
Fig. 1   Refrigerated Case Load Variation with Store Air Humidity

Table 1   Refrigerating Effect (RE) Produced by Open Refrigerated Display Fixtures

Display Fixture Types	RE on Building Per Unit Length of Fixture*			
	Latent Heat, Btu/h·ft	% Latent to Total RE	Sensible Heat, Btu/h·ft	Total RE, Btu/h·ft
Low-temperature (frozen food)				
Single-deck	38	15	207	245
Single-deck/double-island	70	15	400	470
2-deck	144	20	576	720
3-deck	322	20	1288	1610
4- or 5-deck	400	20	1600	2000
Ice cream				
Single-deck	64	15	366	430
Single-deck/double-island	70	15	400	470
Standard-treatment				
Meats				
Single-deck	52	15	298	350
Multideck	219	20	876	1095
Dairy, multideck	196	20	784	980
Produce				
Single-deck	36	15	204	240
Multideck	192	20	768	960

*These figures are general magnitudes for fixtures adjusted for average desired product temperatures and apply to store ambients in front of display cases of 72 to 74°F with 50 to 55% rh. Raising the dry bulb only 3 to 5°F and the humidity to 5 to 10% can increase loads (heat removal) 25% or more. Lower temperatures and humidities, as in winter, have an equally marked effect on lowering loads and heat removal from the space. Consult display case manufactuer's data for the particular equipment to be used.

It is important that the final air-conditioning load be correctly determined. Refer to manufacturers' data for information on total heat extraction, sensible heat, latent heat, and percentage of latent to total loadfor display cases. Engineers report considerable fixture heat removal (case load) variation as the relative humidity and temperature vary in comparatively small increments. Relative humidity above 55% (75°F and 72 gr/lb absolute humidity) substantially increases the load; reduced absolute humidity substantially decreases the load, as shown in Figure 1. Trends in store design, which include more food refrigeration and more efficient lighting, reduce the sensible component of the load even further.

To calculate the total load and percentage of latent and sensible heat that the air conditioning must handle, the refrigerating effect imposed by the display fixtures must be subtracted from the building's gross air-conditioning requirements (Table 1).

Modern supermarket designs have a high percentage of closed refrigerated display fixtures. These vertical cases have large glass display doors and greatly reduce the problem of latent and sensible heat removal from the occupied space. The doors do, however, require heaters to minimize condensation and fogging. These heaters should cycle by automatic control.

For more information on supermarkets, see Chapter 47, Retail Food Store Refrigeration and Equipment, in the 2002 *ASHRAE Handbook—Refrigeration*.

Design Considerations

Store owners and operators frequently complain about cold aisles, heaters that operate even when the outside temperature is above 70°F, and air conditioners that operate infrequently. These problems are usually attributed to spillover of cold air from open refrigerated display equipment.

Although refrigerated display equipment may cause cold stores, the problem is not excessive spillover or improperly operating equipment. Heating and air-conditioning systems must compensate for the effects of open refrigerated display equipment. Design considerations include the following:

- Increased heating requirement because of removal of large quantities of heat, even in summer.

- Net air-conditioning load after deducting the latent and sensible refrigeration effect. The load reduction and change in sensible-latent load ratio have a major effect on equipment selection.
- Need for special air circulation and distribution to offset the heat removed by open refrigerating equipment.
- Need for independent temperature and humidity control.

Each of these problems is present to some degree in every supermarket, although situations vary with climate and store layout. Methods of overcoming these problems are discussed in the following sections. Energy costs may be extremely high if the year-round air-conditioning system has not been designed to compensate for the effects of refrigerated display equipment.

Heat Removed by Refrigerated Displays. The display refrigerator not only cools a displayed product but envelops it in a blanket of cold air that absorbs heat from the room air in contact with it. Approximately 80 to 90% of the heat removed from the room by vertical refrigerators is absorbed through the display opening. Thus, the open refrigerator acts as a large air cooler, absorbing heat from the room and rejecting it via the condensers outside the building. Occasionally, this conditioning effect can be greater than the design air-conditioning capacity of the store. The heat removed by the refrigeration equipment *must* be considered in the design of the air-conditioning and heating systems because this heat is being removed constantly, day and night, summer and winter, regardless of the store temperature.

Display cases increase the building heating requirement such that heat is often required at unexpected times. The following example illustrates the extent of this cooling effect. The desired store temperature is 75°F. Store heat loss or gain is assumed to be 15,000 Btu/h per °F of temperature difference between outside and store temperature. (This value varies with store size, location, and exposure.) The heat removed by refrigeration equipment is 190,000 Btu/h. (This value varies with the number of refrigerators.) The latent heat removed is assumed to be 19% of the total, leaving 81% or 154,000 Btu/h sensible heat removed, which will cool the store 154,000/15,000 = 10°F. By constantly removing sensible heat from its environment, the refrigeration

equipment in this store will cool the store 10°F below outside temperature in winter and in summer. Thus, in mild climates, heat must be added to the store to maintain comfort conditions.

The designer can either discard or reclaim the heat removed by refrigeration. If economics and store heat data indicate that the heat should be discarded, heat extraction from the space must be included in the heating load calculation. If this internal heat loss is not included, the heating system may not have sufficient capacity to maintain design temperature under peak conditions.

The additional sensible heat removed by the cases may change the air-conditioning latent load ratio from 32% to as much as 50% of the net heat load. Removing a 50% latent load by refrigeration alone is very difficult. Normally, it requires specially designed equipment with reheat or chemical adsorption.

Multishelf refrigerated display equipment requires 55% rh or less. In the dry-bulb temperature ranges of average stores, humidity in excess of 55% can cause heavy coil frosting, product zone frosting in low-temperature cases, fixture sweating, and substantially increased refrigeration power consumption.

A humidistat can be used during summer cooling to control humidity by transferring heat from the condenser to a heating coil in the airstream. The store thermostat maintains proper summer temperature conditions. Override controls prevent conflict between the humidistat and the thermostat.

The equivalent result can be accomplished with a conventional air-conditioning system by using three- or four-way valves and reheat condensers in the ducts. This system borrows heat from the standard condenser and is controlled by a humidistat. For higher energy efficiency, specially designed equipment should be considered. Desiccant dehumidifiers and heat pipes have also been used.

Humidity. Cooling from refrigeration equipment does not preclude the need for air conditioning. On the contrary, it increases the need for humidity control.

With increases in store humidity, heavier loads are imposed on the refrigeration equipment, operating costs rise, more defrost periods are required, and the display life of products is shortened. The dew point rises with relative humidity, and sweating can become so profuse that even nonrefrigerated items such as shelving superstructures, canned products, mirrors, and walls may sweat.

Lower humidity results in lower operating costs for refrigerated cases. There are three methods to reduce the humidity level: (1) standard air conditioning, which may overcool the space when the latent load is high and sensible load is low; (2) mechanical dehumidification, which removes moisture by lowering the air temperature to its dew point, and uses hot-gas reheat when needed to discharge at any desired temperature; and (3) desiccant dehumidification, which removes moisture independent of temperature, supplying warm air to the space unless postcooling is provided to discharge at any desired temperature.

Each method provides different dew-point temperatures at different energy consumption and capital expenditures. The designer should evaluate and consider all consequential tradeoffs. Standard air conditioning requires no additional investment but reduces the space dew-point temperature only to 60 to 65°F. At 75°F space temperature this results in 60 to 70% rh at best. Mechanical dehumidifiers can provide humidity levels of 40 to 50% at 75°F. Supply air temperature can be controlled with hot-gas reheat between 50 and 90°F. Desiccant dehumidification can provide levels of 35 to 40% rh at 75°F. Postcooling supply air may be required, depending on internal sensible loads. A desiccant is reactivated by passing hot air at 180 to 250°F through the desiccant base.

System Design. The same air-handling equipment and distribution system are generally used for both cooling and heating. The entrance area is the most difficult section to heat. Many supermarkets in the northern United States are built with vestibules provided with separate heating equipment to temper the cold air entering from outside. Auxiliary heat may also be provided at the checkout

area, which is usually close to the front entrance. Methods of heating entrance areas include the use of (1) air curtains, (2) gas-fired or electric infrared radiant heaters, and (3) waste heat from the refrigeration condensers.

Air-cooled condensing units are the most commonly used in supermarkets. Typically, a central air handler conditions the entire sales area. Specialty areas like bakeries, computer rooms, or warehouses are better served with a separate air handler because the loads in these areas vary and require different control than the sales area.

Most installations are made on the roof of the supermarket. If air-cooled condensers are located on the ground outside the store, they must be protected against vandalism as well as truck and customer traffic. If water-cooled condensers are used on the air-conditioning equipment and a cooling tower is required, provisions should be made to prevent freezing during winter operation.

Air Distribution. Designers overcome the concentrated load at the front of a supermarket by discharging a large portion of the total air supply into the front third of the sales area.

The air supply to the space with a standard air-conditioning system is typically 1 cfm per square foot of sales area. This value should be calculated based on the sensible and latent internal loads. The desiccant system typically requires less air supply because of its high moisture removal rate, typically 0.5 cfm per square foot. Mechanical dehumidification can fall within these parameters, depending on required dew point and suction pressure limitations.

Being denser, air cooled by the refrigerators settles to the floor and becomes increasingly colder, especially in the first 36 in. above the floor. If this cold air remains still, it causes discomfort and does not help to cool other areas of the store that need more cooling. Cold floors or areas in the store cannot be eliminated by the simple addition of heat. Reduction of air-conditioning capacity without circulation of localized cold air is analogous to installing an air conditioner without a fan. To take advantage of the cooling effect of the refrigerators and provide an even temperature in the store, the cold air must be mixed with the general store air.

To accomplish the necessary mixing, air returns should be located at floor level; they should also be strategically placed to remove the cold air near concentrations of refrigerated fixtures. Returns should be designed and located to avoid creating drafts. There are two general solutions to this problem:

- **Return Ducts in Floor.** This is the preferred method and can be accomplished in two ways. The floor area in front of the refrigerated display cases is the coolest area. Refrigerant lines are run to all of these cases, usually in tubes or trenches. If the trenches or tubes are enlarged and made to open under the cases for air return, air can be drawn in from the cold area (Figure 2). The air is returned to the air-handling unit through a tee connection to the trench before it enters the back room area. The opening through which the refrigerant lines enter the back room should be sealed.

  If refrigerant line conduits are not used, air can be returned through inexpensive underfloor ducts. If refrigerators have insufficient undercase air passage, the manufacturer should be consulted. Often they can be raised off the floor approximately 1.5 in. Floor trenches can also be used as ducts for tubing, electrical supply, and so forth.

  Floor-level return relieves the problem of localized cold areas and cold aisles and uses the cooling effect for store cooling, or increases the heating efficiency by distributing the air to areas that need it most.

- **Fans Behind Cases.** If ducts cannot be placed in the floor, circulating fans can draw air from the floor and discharge it above the cases (Figure 3). Although this approach prevents
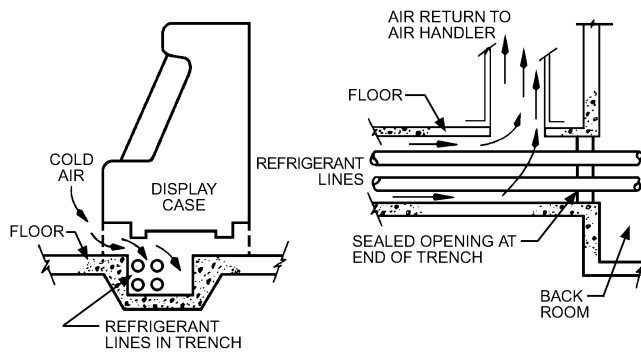
Fig. 2   Floor Return Ducts
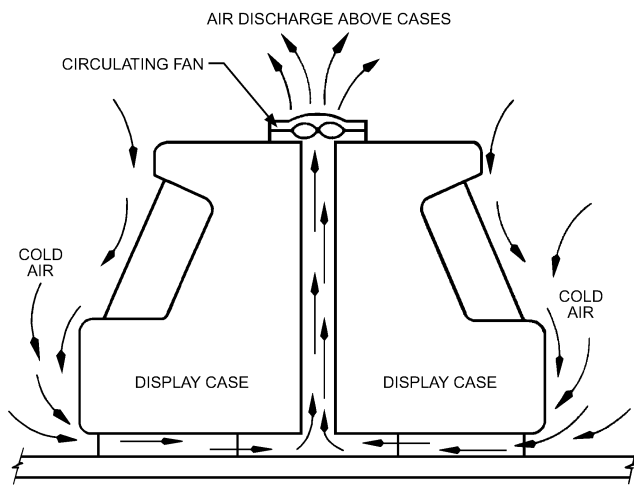
Fig. 3   Air Mixing Using Fans Behind Cases

Fig. 4   Heat Reclaiming Systems

Fig. 5   Machine Room with Automatic Temperature Control Interlocked with Store Temperature Control

objectionable cold aisles in front of the refrigerated display cases, it does not prevent an area with a concentration of refrigerated fixtures from remaining colder than the rest of the store.

Control. Store personnel should only be required to change the position of a selector switch to start or stop the system or to change from heating to cooling or from cooling to heating. Control systems for heat recovery applications are more complex and should be coordinated with the equipment manufacturer.

Maintenance and Heat Reclamation. Most supermarkets, except large chains, do not employ trained maintenance personnel, but rather rely on service contracts with either the installer or a local service company. This relieves store management of the responsibility of keeping the air conditioning operating properly.

Heat extracted from the store and heat of compression may be reclaimed for heating cost saving. One method of reclaiming rejected heat is to use a separate condenser coil located in the air conditioner's air handler, either alternately or in conjunction with the main refrigeration condensers, to provide heat as required (Figure 4). Another system uses water-cooled condensers and delivers its rejected heat to a water coil in the air handler.

The heat rejected by conventional machines using air-cooled condensers may be reclaimed by proper duct and damper design (Figure 5). Automatic controls can either reject this heat to the outside or recirculate it through the store.

DEPARTMENT STORES

Department stores vary in size, type, and location, so air-conditioning design should be specific to each store. An ample minimum quantity of outside air reduces or eliminates odor problems. Essential features of a quality system include (1) an automatic control system properly designed to compensate for load fluctuations, (2) zoned air distribution to maintain uniform conditions under shifting loads, and (3) use of outside air for cooling during intermediate seasons and peak sales periods. It is also desirable to adjust inside temperature for variations in the outside temperature. Although close control of humidity is not necessary, a properly designed system should operate to maintain relative humidity at 50% or below with a corresponding dry-bulb temperature of 78°F. This humidity limit eliminates musty odors and retards perspiration, particularly in fitting rooms.

Load Determination

Because the occupancy (except store personnel) is transient, inside conditions are commonly set not to exceed 78°F db and 50% rh at outside summer design conditions, and 70°F db at outside winter design conditions. Winter humidification is seldom used in store air conditioning.

The number of customers and store personnel normally found on each conditioned floor must be ascertained, particularly in specialty departments or other areas having a greater-than-average concentration of occupants. Lights should be checked for wattage and type. Table 2 gives approximate values for lighting in various areas; Table 3 gives approximate occupancies.

Table 2   Approximate Lighting Load for Department Stores

Area	W/ft²
Basement	3 to 5
First floor	4 to 7
Upper floors, women's wear	3 to 5
Upper floors, house furnishings	2 to 3

Table 3   Approximate Occupancy for Department Stores

Area		ft² per person
Basement		25 to 100
First floor		25 to 75
Upper floors,	women's wear	50 to 100
	house furnishings	100 or more

Other loads, such as those from motors, beauty parlor and restaurant equipment, and any special display or merchandising equipment, should be determined.

The minimum outside air requirement should be as defined in ASHRAE *Standard* 62, which is generally acceptable and adequate for removing odors and keeping the building atmosphere fresh. However, local ventilation ordinances may require greater quantities of outside air.

Paint shops, alteration rooms, rest rooms, eating places, and locker rooms should be provided with positive exhaust ventilation, and their requirements must be checked against local codes.

Design Considerations

Before performing load calculations, the designer should examine the store arrangement to determine what will affect the load and the system design. For existing buildings, actual construction, floor arrangement, and load sources can be surveyed. For new buildings, examination of the drawings and discussion with the architect or owner is required.

Larger stores may contain beauty parlors, restaurants, lunch counters, or auditoriums. These special areas may operate during all store hours. If one of these areas has a load that is small in proportion to the total load, the load may be met by the portion of the air conditioning serving that floor. If present or future operation could for any reason be compromised by such a strategy, this space should be served by separate air conditioning. Because of the concentrated load in the beauty parlor, separate air distribution should be provided for this area.

The restaurant, because of its required service facilities, is generally centrally located. It is often used only during lunchtime. For odor control, a separate air-handling system should be considered. Future plans for the store must be ascertained because they can have a great effect on the type of air conditioning and refrigeration to be used.

System Design. Air conditioning for department stores may be unitary or central station. Selection should be based on owning and operating costs as well as special considerations for the particular store, such as store hours, load variations, and size of load.

Large department stores often use central-station systems consisting of air-handling units having chilled-water cooling coils, hot-water heating coils, fans, and filters. Air systems must have adequate zoning for varying loads, occupancy, and usage. Wide variations in people loads may justify considering variable-volume air distribution systems. Water chilling and heating plants distribute water to the various air handlers and zones and may take advantage of some load diversity throughout the building.

Air-conditioning equipment should not be placed in the sales area; instead, it should be located in ceiling, roof, and mechanical equipment room areas whenever practicable. Maintenance and

operation after installation should be considered when siting equipment.

Air Distribution. All buildings must be studied for orientation, wind exposure, construction, and floor arrangement. These factors affect not only load calculations, but also zone arrangements and duct locations. In addition to entrances, wall areas with significant glass, roof areas, and population densities, the expected locations of various departments (e.g., the lamp department) should be considered. Flexibility must be left in the duct design to allow for future movement of departments. The preliminary duct layout should also be checked in regard to winter heating to determine any special situations. It is usually necessary to design separate air systems for entrances, particularly in northern areas. This is also true for storage areas where cooling is not contemplated.

Air curtains may be installed at entrance doorways to limit or prevent infiltration of unconditioned air, at the same time providing greater ease of entry compared to a vestibule with a second set of doors.

Control. The necessary extent of automatic control depends on the type of installation and the extent to which it is zoned. Control must be such that correctly conditioned air is delivered to each zone. Outside air intake should be automatically controlled to operate at minimum cost while providing required airflow. Partial or full automatic control should be provided for cooling to compensate for load fluctuations. Completely automatic refrigeration plants should be considered.

Maintenance. Most department stores employ personnel for routine operation and maintenance, but rely on service and preventive maintenance contracts for refrigeration cycles, chemical treatment, central plant systems, and major repairs.

Improving Operating Cost. An outside air economizer can reduce the operating cost of cooling in most climates. These are generally available as factory options or accessories with the air-handling units or control systems. Heat recovery and thermal storage should also be analyzed.

CONVENIENCE CENTERS

Many small stores, discount stores, supermarkets, drugstores, theaters, and even department stores are located in convenience centers. The space for an individual store is usually leased. Arrangements for installing air conditioning in leased space vary. Typically, the developer builds a shell structure and provides the tenant with an allowance for usual heating and cooling and other minimum interior finish work. The tenant must then install an HVAC system. In another arrangement, developers install HVAC units in the small stores with the shell construction, often before the space is leased or the occupancy is known. Larger stores typically provide their own HVAC design and installation.

Design Considerations

The developer or owner may establish standards for typical heating and cooling that may or may not be sufficient for the tenant's specific requirements. The tenant may therefore have to install systems of different sizes and types than originally allowed for by the developer. The tenant must ascertain that power and other services will be available for the total intended requirements.

The use of party walls in convenience centers tends to reduce heating and cooling loads. However, the effect an unoccupied adjacent space has on the partition load must be considered.

REGIONAL SHOPPING CENTERS

Regional shopping centers generally incorporate an enclosed, heated and air-conditioned mall. These centers are normally owned by a developer, who may be an independent party, a financial institution, or one of the major tenants in the center.

**Table 4 Typical Installed Cooling Capacity
and Lighting Levels—Midwestern United States**

Type of Space	Area per Unit of Installed Cooling, ft^2/ton	Installed Cooling per Unit of Area, Btu·h/ft^2	Lighting Density of Area, W/ft^2	Annual Lighting Energy Use,[a] kWh/ft^2
Dry retail[b]	367	33	4.0	16.2
Restaurant	136	88	2.0	8.1
Fast food				
food court tenant area	160	75	3.0	12.2
food court seating area	147	82	3.0	12.2
Mall common area	282	43	3.0	12.2[c]
Total	264	45	3.6	14.6

[a]Hours of operating lighting assumes 12 h/day and 6.5 days/week.
[b]Jewelry, high-end lingerie, and some other lighting levels are typically 6 to 8 W/ft^2 and can range to 11 W/ft^2.
[c]5.8 kWh/ft^2 for centers that shut off lighting during daylight, assuming 6 h/day and 6.2 days/week.

Major department stores are typically considered separate buildings, although they are attached to the mall. The space for individual small stores is usually leased. Arrangements for installing air conditioning in the individually leased spaces vary, but are similar to those for small stores in convenience centers.

Table 4 presents typical data that can be used as check figures and field estimates. However, this table should not be used for final determination of load, because the values are only averages.

Design Considerations

The owner provides the air-conditioning system for the enclosed mall. The mall may use a central plant or unitary equipment. The owner generally requires that the individual tenant stores connect to a central plant and includes charges for heating and cooling in the rent. Where unitary systems are used, the owner generally requires that the individual tenant install a unitary system of similar design.

The owner may establish standards for typical heating and cooling systems that may or may not be sufficient for the tenant's specific requirements. Therefore, the tenant may have to install systems of different sizes than originally allowed for by the developer.

Leasing arrangements may include provisions that have a detrimental effect on conservation (such as allowing excessive lighting and outside air or deleting requirements for economizer systems). The designer of HVAC for tenants in a shopping center must be well aware of the lease requirements and work closely with leasing agents to guide these systems toward better energy efficiency.

Many regional shopping centers contain specialty food court areas that require special considerations for odor control, outside air requirements, kitchen exhaust, heat removal, and refrigeration equipment.

System Design. Regional shopping centers vary widely in physical arrangement and architectural design. Single-level and smaller centers usually use unitary systems for mall and tenant air conditioning; multilevel and larger centers usually use a central plant. The owner sets the design of the mall and generally requires that similar systems be installed for tenant stores.

A typical central plant may distribute chilled air to individual tenant stores and to the mall air-conditioning system and use variable-volume control and electric heating at the local use point. Some plants distribute both hot and chilled water. Some all-air systems also distribute heated air. The central plant provides improved efficiency and better overall economics of operation. Central plants also provide the basic components required for smoke control.

Air Distribution. Air distribution for individual stores should be designed for a particular space occupancy. Some tenant stores maintain a negative pressure relative to the mall for odor control.

Air distribution should maintain a slight positive pressure relative to atmospheric pressure and a neutral pressure relative to most of the individual tenant stores. Exterior entrances should have vestibules with independent heating systems.

Smoke management is required by many building codes, so air distribution should be designed to easily accommodate smoke control requirements.

Maintenance. Methods for ensuring the operation and maintenance of HVAC systems in regional shopping centers are similar to those used in department stores. Individual tenant stores may have to provide their own maintenance.

Improving Operating Cost. Methods for lowering operating costs in shopping centers are similar to those used in department stores. Some shopping centers have successfully used cooling tower heat exchanger economizers.

Central plant systems for regional shopping centers typically have much lower operating costs than unitary systems. However, the initial cost of the central plant system is typically higher.

MULTIPLE-USE COMPLEXES

Multiple-use complexes are being developed in most metropolitan areas. These complexes generally combine retail facilities with other facilities such as offices, hotels, residences, or other commercial space into a single site. This consolidation of facilities into a single site or structure provides benefits such as improved land use; structural savings; more efficient parking; utility savings; and opportunities for more efficient electrical, fire protection, and mechanical systems.

Load Determination

The various occupancies may have peak HVAC demands that occur at different times of the day or even of the year. Therefore, the HVAC loads of these occupancies should be determined independently. Where a combined central plant is considered, a block load should also be determined.

Design Considerations

Retail facilities are generally located on the lower levels of multiple-use complexes, and other commercial facilities are on upper levels. Generally, the perimeter loads of the retail portion differ from those of the other commercial spaces. Greater lighting and population densities also make HVAC demands for the retail space different from those for the other commercial space.

The differences in HVAC characteristics for various occupancies within a multiple-use complex indicate that separate air handling and distribution should be used for the separate spaces. However, combining the heating and cooling requirements of various facilities into a central plant can achieve a substantial saving. A combined central heating and cooling plant for a multiple-use complex also provides good opportunities for heat recovery, thermal storage, and other similar functions that may not be economical in a single-use facility.

Many multiple-use complexes have atriums. The stack effect created by atriums requires special design considerations for tenants and space on the main floor. Areas near entrances require special measures to prevent drafts and accommodate extra heating requirements.

System Design. Individual air-handling and distribution systems should be designed for the various occupancies. The central heating and cooling plant may be sized for the block load requirements, which may be less than the sum of each occupancy's demand.

Control. Multiple-use complexes typically require centralized control. It may be dictated by requirements for fire and smoke control, security, remote monitoring, billing for central facilities use, maintenance control, building operations control, and energy management.

CHAPTER 3

COMMERCIAL AND PUBLIC BUILDINGS

THIS chapter summarizes load characteristics and both general and specific design criteria that apply to commercial buildings. Design criteria include such factors as comfort level; cost; and fire, smoke, and odor control. Chapter 4 contains discussion on houses of worship, arenas and stadiums, auditoriums, convention centers, natatoriums, and other places of assembly. Museums, galleries, libraries, and archives are covered in Chapter 21.

GENERAL CRITERIA

In theory, most systems, if properly applied, can be successful in any building. However, in practice, factors such as initial and operating costs, space allocation, architectural design, location, and the engineer's evaluation and experience limit the proper choices for a given building type.

Heating and air-conditioning systems that are simple in design and of the proper size for a given building generally have fairly low maintenance and operating costs. For optimum results, as much inherent thermal control as is economically possible should be built into the basic structure. The relationship between the shape, orientation, and air-conditioning capacity of a building should also be considered. Because the exterior load may vary from 30 to 60% of the total air-conditioning load when the fenestration area ranges from 25 to 75% of the exterior envelope surface area, it may be desirable to minimize the perimeter area. For example, a rectangular building with a four-to-one aspect ratio requires substantially more refrigeration than a square building with the same floor area.

Building size, shape, and component selection are normally determined by the building architect and/or owner. Changing any of these parameters to reach optimum results requires cooperation among these individuals or groups.

Proper design also considers controlling noise and minimizing pollution of the atmosphere and water systems around the building.

Retrofitting existing buildings is also an important part of the construction industry because of increased costs of construction and the necessity of reducing energy consumption. Table 1 lists factors to consider before selecting a system for any building. Selection is often made by the owner and may not be based on an engineering study. To a great degree, system selection is based on the engineer's ability to relate factors involving higher first cost or lower life-cycle cost and benefits that have no calculable monetary value.

Some buildings are constructed with only heating and ventilating systems. For these buildings, greater design emphasis should be placed on natural or forced ventilation systems to minimize occupant discomfort during hot weather. To provide for future cooling, humidification, or both, the design principles are the same as those for a fully air-conditioned building.

Load Characteristics

Load characteristics for the building must be understood to ensure that systems respond adequately at part load as well as at full load. Systems must be able to respond to load fluctuations based on the combination of occupancy variations, process load shifts, solar load variations, and atmospheric weather conditions (e.g., temperature and humidity changes). Some building loads may be brief and infrequent, such as an annual meeting of a large group in a conference room, whereas others may be more constant and long-lasting, such as operation of data processing equipment.

Analysis of any building for heat recovery or total energy systems requires sufficient load profile and load duration information on all forms of building input to (1) properly evaluate the instantaneous effect of one on the other when no energy storage is contemplated and (2) evaluate short-term effects (up to 48 h) when energy storage is used.

Load profile curves consist of appropriate energy loads plotted against the time of day. Load duration curves indicate the accumulated number of hours at each load condition, from the highest to the lowest load for a day, a month, or a year. The area under load profile and load duration curves for corresponding periods is equivalent to the load multiplied by the time. These calculations must consider the type of air and water distribution systems in the building.

Load profiles for two or more energy forms during the same operating period may be compared to determine load-matching characteristics under diverse operating conditions. For example, when thermal energy is recovered from a diesel electric generator at a rate equal to or less than the thermal energy demand, the energy can be used instantaneously, avoiding waste. It may be worthwhile to store thermal energy when it is generated at a greater rate than demanded. A load profile study helps determine the economics of thermal storage.

Similarly, with internal source heat recovery, load matching must be integrated over the operating season with the aid of load duration curves for overall feasibility studies. These curves are useful in energy consumption analysis calculations as a basis for hourly input values in computer programs (see Chapter 32 of the 2005 *ASHRAE Handbook—Fundamentals*).

Aside from environmental considerations, the economic feasibility of district heating and cooling is influenced by load density and diversity factors for branch feeds to buildings along distribution mains. For example, the load density or energy per unit length of distribution main can be small enough in a complex of low-rise, lightly loaded buildings located at a considerable distance from one another, to make a central heating, cooling, or heating and cooling plant uneconomical.

Concentrations of internal loads peculiar to each application are covered later in this chapter and in Chapters 29, 30, and 31 of the 2005 *ASHRAE Handbook—Fundamentals*.
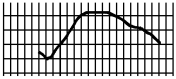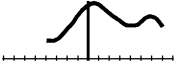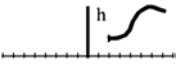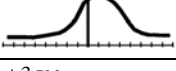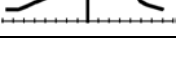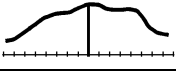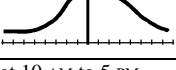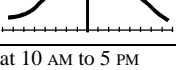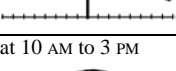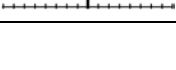
The preparation of this chapter is assigned to TC 9.8, Large Building Air-Conditioning Applications.

Table 1   General Design Criteria[a, b]

General Category	Specific Category	Inside Design Conditions		Air Movement	Circulation, ach
		Winter	Summer		
Dining and Entertainment Centers	Cafeterias and Luncheonettes	70 to 74°F 20 to 30% rh	78°F[d] 50% rh	50 fpm at 6 ft above floor	12 to 15
	Restaurants	70 to 74°F 20 to 30% rh	74 to 78°F 55 to 60% rh	25 to 30 fpm	8 to 12
	Bars	70 to 74°F 20 to 30% rh	74 to 78°F 50 to 60% rh	30 fpm at 6 ft above floor	15 to 20
	Nightclubs and Casinos	70 to 74°F 20 to 30% rh	74 to 78°F 50 to 60% rh	below 25 fpm at 5 ft above floor	20 to 30
	Kitchens	70 to 74°F	85 to 88°F	30 to 50 fpm	12 to 15[g]
Office Buildings		70 to 74°F 20 to 30% rh	74 to 78°F 50 to 60% rh	25 to 45 fpm 0.75 to 2 cfm/ft^2	4 to 10
Museums, Galleries, Libraries, and Archives (also see Chapter 21)	Average	68 to 72°F 40 to 55% rh		below 25 fpm	8 to 12
	Archival	See Chapter 21		below 25 fpm	8 to 12
Bowling Centers		70 to 74°F 20 to 30% rh	75 to 78°F 50 to 55% rh	50 fpm at 6 ft above floor	10 to 15
Communication Centers	Telephone Terminal Rooms	72 to 78°F 40 to 50% rh	72 to 78°F 40 to 50% rh	25 to 30 fpm	8 to 20
	Radio and Television Studios	74 to 78°F 30 to 40% rh	74 to 78°F 40 to 55% rh	below 25 fpm at 12 ft above floor	15 to 40
Transportation Centers (also see Chapter 13)	Airport Terminals	70 to 74°F 20 to 30% rh	74 to 78°F 50 to 60% rh	25 to 30 fpm at 6 ft above floor	8 to 12
	Ship Docks	70 to 74°F 20 to 30% rh	74 to 78°F 50 to 60% rh	25 to 30 fpm at 6 ft above floor	8 to 12
	Bus Terminals	70 to 74°F 20 to 30% rh	74 to 78°F 50 to 60% rh	25 to 30 fpm at 6 ft above floor	8 to 12
	Garages[j]	40 to 55°F	80 to 100°F	30 to 75 fpm	4 to 6
Warehouses		Inside design temperatures for warehouses often depend on the materials stored			1 to 4

Table 1 General Design Criteria[a, b] (*Concluded*)

Noise[c]	Filtering Efficiencies (ASHRAE *Standard* 52.1)	Load Profile	Comments
NC 40 to 50[e]	35% or better	Peak at 1 to 2 PM	Prevent draft discomfort for patrons waiting in serving lines
NC 35 to 40	35% or better	Peak at 1 to 2 PM	
NC 35 to 50	Use charcoal for odor control with manual purge control for 100% outside air to exhaust ±35% prefilters	Peak at 5 to 7 PM	
NC 35 to 45[f]	Use charcoal for odor control with manual purge control for 100% outside air to exhaust ±35% prefilters	Nightclubs peak at 8 PM to 2 AM Casinos peak at 4 PM to 2 AM Equipment, 24 h/day	Provide good air movement but prevent cold draft discomfort for patrons
NC 40 to 50	10 to 15% or better		Negative air pressure required for odor control (also see Chapter 31)
NC 30 to 45	35 to 60% or better	Peak at 4 PM	
NC 35 to 40	35 to 60% or better	Peak at 3 PM	
NC 35	35% prefilters plus charcoal filters 85 to 95% final[i]	Peak at 3 PM	
NC 40 to 50	10 to 15%	Peak at 6 to 8 PM	
to NC 60	85% or better	Varies with location and use	Constant temperature and humidity required
NC 15 to 25	35% or better	Varies widely because of changes in lighting and people	Constant temperature and humidity required
NC 35 to 50	35% or better and charcoal filters	Peak at 10 AM to 9 PM	Positive air pressure required in terminal
NC 35 to 50	10 to 15%	Peak at 10 AM to 5 PM	Positive air pressure required in waiting area
NC 35 to 50	35% with exfiltration	Peak at 10 AM to 5 PM	Positive air pressure required in terminal
NC 35 to 50	10 to 15%	Peak at 10 AM to 5 PM	Negative air pressure required to remove fumes; positive air in pressure adjacent occupied spaces
to NC 75	10 to 35%	Peak at 10 AM to 3 PM	

Notes to Table 1, General Design Criteria

[a]This table shows design criteria differences between various commercial and public buildings. It should not be used as sole source for design criteria. Each type of data contained here can be determined from *ASHRAE Handbook* and standards.

[b]Consult governing codes to determine minimum allowable requirements. Outside air requirements may be reduced if high-efficiency adsorption equipment or other odor- or gas-removal equipment is used. See ASHRAE *Standard* 62 for calculation procedures. Also see Chapter 45 in this volume and Chapter 13 of the 2005 *ASHRAE Handbook—Fundamentals*.

[c]Refer to Chapter 47.

[d]Food in these areas is often eaten more quickly than in a restaurant; therefore, turnover of diners is much faster. Because diners seldom remain for long periods, they do not require the degree of comfort necessary in restaurants. Thus, it may be possible to lower design criteria standards and still provide reasonably comfortable conditions. Although space conditions of 80°F and 50% rh may be satisfactory for patrons when it is 95°F and 50% rh outside, inside conditions of 78°F and 40% rh are better.

[e]Cafeterias and luncheonettes usually have some or all food preparation equipment and trays in the same room with diners. These establishments are generally noisier than restaurants, so noise transmission from air-conditioning equipment is not as critical.

[f]In some nightclubs, air-conditioning system noise must be kept low so patrons can hear the entertainment.

[g]Usually determined by kitchen hood requirements.

[h]Peak kitchen heat load does not generally occur at peak dining load, although in luncheonettes and some cafeterias where cooking is done in dining areas, peaks may be simultaneous.

[i]Methods for removing chemical pollutants must also be considered.

[j]Also includes service stations.

Design Concepts

If a structure is characterized by several exposures and multipurpose use, especially with wide load swings and noncoincident energy use in certain areas, multiunit or unitary systems may be considered for such areas, but not necessarily for the entire building. The benefits of transferring heat absorbed by cooling from one area to other areas, processes, or services that require heat may enhance the selection of such systems. Systems such as incremental closed-loop heat pumps may be cost-effective.

When the cost of energy is included in the rent with no means for permanent or checkmetering, tenants tend to consume excess energy. This energy waste raises operating costs for the owner, decreases profitability, and has a detrimental effect on the environment. Although design features can minimize excess energy penalties, they seldom eliminate waste. For example, U.S. Department of Housing and Urban Development nationwide field records for total-electric housing show that rent-included dwellings use approximately 20% more energy than those directly metered by a public utility company.

Diversity factor benefits for central heating and cooling in rent-included buildings may result in lower building demand and connected loads. However, energy waste may easily result in load factors and annual energy consumption exceeding that of buildings where the individual has a direct economic incentive to reduce energy consumption. Heat flow (Btu) meters should be considered for charging for energy consumption.

Design Criteria

In many applications, design criteria are fairly evident, but in all cases, the engineer should understand the owner's and user's intent because any single factor may influence system selection. The engineer's experience and judgment in projecting future needs may be a better criterion for system design than any other single factor.

Comfort Level. Comfort, as measured by temperature, humidity, air motion, air quality, noise, and vibration, is not identical for all buildings, occupant activities, or uses of space. Control of static electricity may be a consideration in humidity control.

Costs. Owning and operating costs can affect system selection and seriously conflict with other criteria. Therefore, the engineer must help the owner resolve these conflicts by considering factors such as cost and availability of different fuels, ease of equipment access, and maintenance requirements.

Local Conditions. Local, state, and national codes, regulations, and environmental concerns must be considered in design. Chapters 27 and 28 of the 2005 *ASHRAE Handbook—Fundamentals* give information on calculating the effects of weather in specific areas.

Automatic Temperature Control. Proper automatic temperature control maintains occupant comfort during varying internal and external loads. Improper temperature control may mean a loss of customers in restaurants and other public buildings. An energy management control system can be combined with a building automation system to allow the owner to manage energy, lighting,

security, fire protection, and other similar systems from one central control point. Chapters 35 and 46 include more details.

Fire, Smoke, and Odor Control. Fire and smoke can easily spread through elevator shafts, stairwells, ducts, and other routes. Although an air-conditioning system can spread fire and smoke by (1) fan operation, (2) penetrations required in walls or floors, or (3) the stack effect without fan circulation, a properly designed and installed system can be a positive means of fire and smoke control.

Chapter 52 has information on techniques for positive control after a fire starts. Effective attention to fire and smoke control also helps prevent odor migration into unventilated areas (see Chapter 45). Ventilation system design should consider applicable National Fire Protection Association standards, especially NFPA *Standards* 90A and 96.

DINING AND ENTERTAINMENT CENTERS

Load Characteristics

Air conditioning restaurants, cafeterias, bars, and nightclubs presents common load problems encountered in comfort conditioning, with additional factors pertinent to dining and entertainment applications. Such factors include

- Extremely variable loads with high peaks, in many cases, occurring twice daily
- High sensible and latent heat gains because of gas, steam, electric appliances, people, and food
- Sensible and latent loads that are not always coincident
- Large quantities of makeup air normally required
- Localized high sensible and latent heat gains in dancing areas
- Unbalanced conditions in restaurant areas adjacent to kitchens, which, although not part of the conditioned space, still require special attention
- Heavy infiltration of outside air through doors during rush hours
- Smoking versus nonsmoking areas

Internal heat and moisture loads come from occupants, motors, lights, appliances, and infiltration. Separate calculations should be made for patrons and employees. The sensible and latent heat load must be proportioned in accordance with the design temperature selected for both sitting and working people, because the latent-to-sensible heat ratio for each category decreases as room temperature decreases.

Hoods required to remove heat from appliances may also substantially reduce the space latent loads.

Infiltration is a considerable factor in many restaurants because of short occupancy and frequent door use. It is increased by the need for large quantities of makeup air, which should be provided mechanically to replace air exhausted through hoods and for smoke removal. Systems for hood exhaust makeup should concentrate on exhausting nonconditioned and minimally heated makeup air. Wherever possible, vestibules or revolving doors should be installed to reduce infiltration.

Design Concepts

The following factors influence system design and equipment selection:

- High concentrations of food, body, and tobacco-smoke odors require adequate ventilation with proper exhaust facilities.
- Step control of refrigeration plants gives satisfactory and economical operation under reduced loads.
- Exhausting air at the ceiling removes smoke and odor.
- Building design and space limitations often favor one equipment type over another. For example, in a restaurant having a vestibule with available space above it, air conditioning with condensers and evaporators remotely located above the vestibule may be satisfactory. Such an arrangement saves valuable space, even though self-contained units located within the conditioned space may be somewhat lower in initial and maintenance costs. In general, small cafeterias, bars, and the like, with loads up to 10 tons, can be most economically conditioned with packaged units; larger and more elaborate establishments require central plants.
- Smaller restaurants with isolated plants usually use direct-expansion systems.
- Mechanical humidification is typically not provided because of high internal latent loads.
- Some air-to-air heat recovery equipment can reduce the energy required for heating and cooling ventilation air. Chapter 44 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment* includes details. The potential for grease condensation on heat recovery surfaces must also be considered.
- A vapor compression or desiccant-based dehumidifier should be considered for makeup air handling and enhanced humidity control.

Because eating and entertainment centers generally have low sensible heat factors and require high ventilation rates, fan-coil and induction systems are usually not applicable. All-air systems are more suitable. Space must be established for ducts, except for small systems with no ductwork. Large establishments are often served by central chilled-water systems.

In cafeterias and luncheonettes, the air distribution system must keep food odors at the serving counters away from areas where patrons are eating. This usually means heavy exhaust air requirements at the serving counters, with air supplied into, and induced from, eating areas. Exhaust air must also remove the heat from hot trays, coffee urns, and ovens to minimize patron and employee discomfort and to reduce air-conditioning loads. These factors often create greater air-conditioning loads for cafeterias and luncheonettes than for restaurants.

Odor Removal. Transferring air from dining areas into the kitchen keeps odors and heat out of dining areas and cools the kitchen. Outside air intake and kitchen exhaust louvers should be located so that exhaust air is neither drawn back into the system nor allowed to cause discomfort to passersby.

Where odors can be drawn back into dining areas, activated charcoal filters, air washers, or ozonators are used to remove odors. Kitchen, locker room, toilet, or other malodorous air should not be recirculated unless air purifiers are used.

Kitchen Air Conditioning. If planned in the initial design phases, kitchens can often be air conditioned effectively without excessive cost. It is not necessary to meet the same design criteria as for dining areas, but kitchen temperatures can be reduced significantly. The relatively large number of people and food loads in dining and kitchen areas produce a high latent load. Additional cooling required to eliminate excess moisture increases refrigeration plant, cooling coil, and air-handling equipment size.

Advantageously located self-contained units, with air distribution designed so as not to produce drafts off hoods and other equipment, can be used to spot-cool intermittently. High-velocity air distribution may be effective. Costs are not excessive, and kitchen personnel efficiency can be improved greatly.

Even in climates with high wet-bulb temperatures, direct or indirect evaporative cooling may be a good compromise between the expense of air conditioning and lack of comfort in ventilated kitchens. For more information, see Chapter 31, Kitchen Ventilation.

Special Considerations

In establishing design conditions, the duration of individual patron occupancy should be considered. Patrons entering from outside are more comfortable in a room with a high temperature than those who remain long enough to become acclimated. Nightclubs and deluxe restaurants are usually operated at a lower effective temperature than cafeterias and luncheonettes.

Often, the ideal design condition must be rejected for an acceptable condition because of equipment cost or performance limitations. Restaurants are frequently affected in this way because ratios of latent to sensible heat may result in uneconomical or oversized equipment selection, unless an enhanced dehumidification system or a combination of lower design dry-bulb temperature and higher relative humidity (which gives an equal effective temperature) is selected.

In severe climates, entrances and exits in any dining establishment should be completely shielded from diners to prevent drafts. Vestibules provide a measure of protection. However, both vestibule doors are often open simultaneously. Revolving doors or local means for heating or cooling infiltration air may be provided to offset drafts.

Uniform employee comfort is difficult to maintain because of (1) temperature differences between the kitchen and dining room and (2) the constant motion of employees. Because customer satisfaction is essential to a dining establishment's success, patron comfort is the primary consideration. However, maintaining satisfactory temperature and atmospheric conditions for customers also helps alleviate employee discomfort.

One problem in dining establishments is the use of partitions to separate areas into modular units. Partitions create such varied load conditions that individual modular unit control is generally necessary.

Baseboard radiation or convectors, if required, should be located so as not to overheat patrons. This is difficult to achieve in some layouts because of movable chairs and tables. For these reasons, it is desirable to enclose all dining room and bar heating elements in insulated cabinets with top outlet grilles and baseboard inlets. With heating elements located under windows, this practice has the additional advantage of directing the heat stream to combat window downdraft and air infiltration. Separate smoking and nonsmoking areas may be required. The smoking area should be exhausted or served by separate air-handling equipment. Air diffusion device selection and placement should minimize smoke migration toward nonsmoking areas. Smoking areas must have a negative air pressure relationship with adjacent occupied areas.

Restaurants. In restaurants, people are seated and served at tables, and food is generally prepared in remote areas. This type of dining is usually enjoyed in a leisurely and quiet manner, so the ambient atmosphere should be such that the air conditioning is not noticed. Where specialized or open cooking is a feature, provisions should be made for control and handling of cooking odors and smoke.

Bars. Bars are often a part of a restaurant or nightclub. If they are establishments on their own, they often serve food as well as drinks, and they should be classified as restaurants with food preparation in remote areas. Alcoholic beverages produce pungent vapors, which must be drawn off. In addition, smoking at bars (when allowed) is generally considerably heavier than in restaurants. Therefore, outside air requirements are relatively high by comparison.

Nightclubs and Casinos. Both nightclubs and casinos may include a restaurant, bar, stage, and dancing area. The bar should be treated as a separately zoned area, with its own supply and exhaust system. People in the restaurant area who dine and dance may require twice the air changes and cooling required by patrons who dine and then watch a show. The length of stay generally exceeds that encountered in most eating places. In addition, eating in nightclubs and casinos is usually secondary to drinking and smoking (when allowed). Patron density usually exceeds that of conventional eating establishments.

Kitchens. The kitchen has the greatest concentration of noise, heat load, smoke, and odors; ventilation is the chief means of removing these objectionable elements and preventing them from entering dining areas. To ensure odor control, kitchen air pressure should be kept negative relative to other areas. Maintenance of reasonably comfortable working conditions is important. For more information, see Chapter 31.

OFFICE BUILDINGS

Load Characteristics

Office buildings usually include both peripheral and interior zone spaces. The peripheral zone extends 10 to 12 ft inward from the outer wall toward the interior of the building and frequently has a large window area. These zones may be extensively subdivided. Peripheral zones have variable loads because of changing sun position and weather. These zone areas typically require heating in winter. During intermediate seasons, one side of the building may require cooling, while another side requires heating. However, the interior zone spaces usually require a fairly uniform cooling rate throughout the year because their thermal loads are derived almost entirely from lights, office equipment, and people. Interior space conditioning is often by systems that have variable-air-volume control for low- or no-load conditions.

Most office buildings are occupied from approximately 8:00 AM to 6:00 PM; many are occupied by some personnel from as early as 5:30 AM to as late as 7:00 PM. Some tenants' operations may require night work schedules, usually not beyond 10:00 PM. Office buildings may contain printing plants, communications operations, broadcasting studios, and computing centers, which could operate 24 h per day. Therefore, for economical air-conditioning design, the intended uses of an office building must be well established before design development.

Occupancy varies considerably. In accounting or other sections where clerical work is done, the maximum density is approximately one person per 75 ft^2 of floor area. Where there are private offices, the density may be as little as one person per 200 ft^2. The most serious cases, however, are the occasional waiting rooms, conference rooms, or directors' rooms where occupancy may be as high as one person per 20 ft^2.

The lighting load in an office building is a significant part of the total heat load. Lighting and normal equipment electrical loads average from 1 to 5 W/ft^2 but may be considerably higher, depending on the type of lighting and amount of equipment. Buildings with computer systems and other electronic equipment can have electrical loads as high as 5 to 10 W/ft^2 An accurate appraisal should be made of the amount, size, and type of computer equipment anticipated for the life of the building to size the air-handling equipment properly and provide for future installation of air-conditioning apparatus.

About 30% of the total lighting heat output from recessed fixtures can be withdrawn by exhaust or return air and, therefore, kept out of space-conditioning supply air requirements. By connecting a duct to each fixture, the most balanced air system can be provided. However, this method is expensive, so the suspended ceiling is often used as a return air plenum with air drawn from the space to above the suspended ceiling.

Miscellaneous allowances (for fan heat, duct heat pickup, duct leakage, and safety factors) should not exceed 12% of the total load.

Building shape and orientation are often determined by the building site, but certain variations in these factors can increase refrigeration load by 10 to 15%. Shape and orientation should therefore be carefully analyzed in the early design stages.

Design Concepts

The variety of functions and range of design criteria applicable to office buildings have allowed the use of almost every available air-conditioning system. Multistory structures are discussed here, but the principles and criteria are similar for all sizes and shapes of office buildings.

Attention to detail is extremely important, especially in modular buildings. Each piece of equipment, duct and pipe connections, and the like may be duplicated hundreds of times. Thus, seemingly minor design variations may substantially affect construction and operating costs. In initial design, each component must be analyzed not only as an entity, but also as part of an integrated system. This systems design approach is essential for achieving optimum results.

There are several classes of office buildings, determined by the type of financing required and the tenants who will occupy the building. Design evaluation may vary considerably based on specific tenant requirements; it is not enough to consider typical floor patterns only. Many larger office buildings include stores, restaurants, recreational facilities, data centers, telecommunication centers, radio and television studios, and observation decks.

Built-in system flexibility is essential for office building design. Business office procedures are constantly being revised, and basic building services should be able to meet changing tenant needs.

The type of occupancy may have an important bearing on air distribution system selection. For buildings with one owner or lessee, operations may be defined clearly enough that a system can be designed without the degree of flexibility needed for a less well-defined operation. However, owner-occupied buildings may require considerable design flexibility because the owner will pay for all alterations. The speculative builder can generally charge alterations to tenants. When different tenants occupy different floors, or even parts of the same floor, the degree of design and operation complexity increases to ensure proper environmental comfort conditions to any tenant, group of tenants, or all tenants at once. This problem is more acute if tenants have seasonal and variable overtime schedules.

Stores, banks, restaurants, and entertainment facilities may have hours of occupancy or design criteria that differ substantially from those of office buildings; therefore, they should have their own air distribution systems and, in some cases, their own heating and/or refrigeration equipment.

Main entrances and lobbies are sometimes served by a separate system because they buffer the outside atmosphere and the building interior. Some engineers prefer to have a lobby summer temperature 4 to 6°F above office temperature to reduce operating cost and the temperature shock to people entering or leaving the building.

The unique temperature and humidity requirements of data processing installations and the fact that they often run 24 h per day for extended periods generally warrant separate refrigeration and air distribution systems. Separate backup systems may be required for data processing areas in case the main building HVAC system fails. Chapter 17 has further information.

The degree of air filtration required should be determined. Service cost and effect of air resistance on energy costs should be analyzed for various types of filters. Initial filter cost and air pollution characteristics also need to be considered. Activated charcoal filters for odor control and reduction of outside air requirements are another option to consider.

Providing office buildings with continuous 100% outside air is seldom justified; therefore, most office buildings are designed to

minimize outside air use, except during economizer operation. However, attention to inside air quality may dictate higher levels of ventilation air. In addition, the minimum volume of outside air should be maintained in variable-volume air-handling systems. Dry-bulb or enthalpy-controlled economizer cycles should be considered for reducing energy costs.

When an economizer cycle is used, systems should be zoned so that energy is not wasted by heating outside air. This is often accomplished by a separate air distribution system for the interior and each major exterior zone.

High-rise office buildings have traditionally used perimeter dual-duct, induction, or fan-coil systems. Where fan-coil or induction systems have been installed at the perimeter, separate all-air systems have generally been used for the interior. Variable-air-volume systems, including modulated air diffusers and self-contained perimeter unit systems, have also been used. If variable-air-volume systems serve the interior, perimeters are usually served by variable-volume or dual-duct systems supplemented with fan-powered terminals, terminals with reheat coils, or radiation (ceiling panels or baseboard). The perimeter systems can be hydronic or electric.

Many office buildings without an economizer cycle have a bypass multizone unit installed on each floor or several floors with a heating coil in each exterior zone duct. Variable-air-volume variations of the bypass multizone and other floor-by-floor, all-air systems are also being used. These systems are popular because of their low fan power and initial cost, and energy savings from independent operating schedules, which are possible between floors occupied by tenants with different operating hours.

Perimeter radiation or infrared systems with conventional, single-duct, low-velocity air conditioning that furnishes air from packaged air-conditioning units or multizone units may be more economical for small office buildings. The need for a perimeter system, which is a function of exterior glass percentage, external wall thermal value, and climate severity, should be carefully analyzed.

A perimeter heating system separate from the cooling system is preferable, because air distribution devices can then be selected for a specific duty rather than as a compromise between heating and cooling performance. The higher cost of additional air-handling or fan-coil units and ductwork may lead the designer to a less expensive option, such as fan-powered terminal units with heating coils serving perimeter zones in lieu of a separate heating system. Radiant ceiling panels for the perimeter zones are another option.

Interior space usage usually requires that interior air-conditioning systems allow modification to handle all load situations. Variable-air-volume systems are often used. When using these systems, low-load conditions should be carefully evaluated to determine whether adequate air movement and outside air can be provided at the proposed supply air temperature without overcooling. Increases in supply air temperature tend to nullify energy savings in fan power, which are characteristic of variable-air-volume systems. Low-temperature air distribution for additional savings in transport energy is seeing increased use, especially when coupled with an ice storage system.

In small to medium-sized office buildings, air-source heat pumps may be chosen. In larger buildings, internal-source heat pump systems (water-to-water) are feasible with most types of air-conditioning systems. Heat removed from core areas is rejected to either a cooling tower or perimeter circuits. The internal-source heat pump can be supplemented by a central heating system or electrical coils on extremely cold days or over extended periods of limited occupancy. Removed excess heat may also be stored in hot-water tanks.

Many heat recovery or internal-source heat pump systems exhaust air from conditioned spaces through lighting fixtures. Approximately 30% of lighting heat can be removed in this manner. This reduces required air quantities, and extends lamp life by providing a much cooler ambient operating environment.

Suspended-ceiling return air plenums eliminate sheet metal return air ductwork to reduce floor-to-floor height requirements. However, suspended-ceiling plenums may increase the difficulty of proper air balancing throughout the building. Problems often connected with suspended ceiling return plenums include

- Air leakage through cracks, with resulting smudges
- Tendency of return air openings nearest to a shaft opening or collector duct to pull too much air, thus creating uneven air motion and possible noise
- Noise transmission between office spaces

Air leakage can be minimized by proper workmanship. To overcome drawing too much air, return air ducts can be run in the suspended ceiling pathway from the shaft, often in a simple radial pattern. Ends of the ducts can be left open or dampered. Generous sizing of return air grilles and passages lowers the percentage of circuit resistance attributable to the return air path. This bolsters effectiveness of supply air balancing devices and reduces the significance of air leakage and drawing too much air. Structural blockage can be solved by locating openings in beams or partitions with fire dampers, where required.

Spatial Requirements

Total office building electromechanical space requirements vary tremendously based on types of systems planned; however, the average is approximately 8 to 10% of the gross area. Clear height required for fan rooms varies from approximately 10 to 18 ft, depending on the distribution system and equipment complexity. On office floors, perimeter fan-coil or induction units require approximately 1 to 3% of the floor area. Interior air shafts and pipe chases require approximately 3 to 5% of the floor area. Therefore, ducts, pipes, and equipment require approximately 4 to 8% of each floor's gross area.

Where large central units supply multiple floors, shaft space requirements depend on the number of fan rooms. In such cases, one mechanical equipment room usually furnishes air requirements for 8 to 20 floors (above and below for intermediate levels), with an average of 12 floors. The more floors served, the larger the duct shafts and equipment required. This results in higher fan room heights and greater equipment size and mass.

The fewer floors served by an equipment room, the greater the flexibility in serving changing floor or tenant requirements. Often, one mechanical equipment room per floor and complete elimination of vertical shafts requires no more total floor area than fewer larger mechanical equipment rooms, especially when there are many small rooms and they are the same height as typical floors. Equipment can also be smaller, although maintenance costs are higher. Energy costs may be reduced with more equipment rooms serving fewer areas, because equipment can be shut off in unoccupied areas, and high-pressure ductwork is not required. Equipment rooms on upper levels generally cost more to install because of rigging and transportation logistics.

In all cases, mechanical equipment rooms must be thermally and acoustically isolated from office areas.

Cooling Towers. Cooling towers are the largest single piece of equipment required for air-conditioning systems. Cooling towers require approximately 1 ft^2 of floor area per 400 ft^2 of total building area and are 13 to 40 ft high. When towers are located on the roof, the building structure must be able to support the cooling tower and dunnage, full water load (approximately 120 to 150 lb/ft^2), and seismic and wind load stresses.

Where cooling tower noise may affect neighboring buildings, tower design should include sound traps or other suitable noise baffles. This may affect tower space, mass of the units, and motor power. Slightly oversizing cooling towers can reduce noise and power consumption because of lower speeds, but may increase initial cost.

Cooling towers are sometimes enclosed in a decorative screen for aesthetic reasons; therefore, calculations should ascertain that the screen has sufficient free area for the tower to obtain its required air quantity and to prevent recirculation.

If the tower is placed in a rooftop well or near a wall, or split into several towers at various locations, design becomes more complicated, and initial and operating costs increase substantially. Also, towers should not be split and placed on different levels because hydraulic problems increase. Finally, the cooling tower should be built high enough above the roof so that the bottom of the tower and the roof can be maintained properly.

Special Considerations

Office building areas with special ventilation and cooling requirements include elevator machine rooms, electrical and telephone closets, electrical switchgear, plumbing rooms, refrigeration rooms, and mechanical equipment rooms. The high heat loads in some of these rooms may require air-conditioning units for spot cooling.

In larger buildings with intermediate elevator, mechanical, and electrical machine rooms, it is desirable to have these rooms on the same level or possibly on two levels. This may simplify horizontal ductwork, piping, and conduit distribution systems and allow more effective ventilation and maintenance of these equipment rooms.

An air-conditioning system cannot prevent occupants at the perimeter from feeling direct sunlight. Venetian blinds and drapes are often provided but seldom used. External shading devices (screens, overhangs, etc.) or reflective glass are preferable.

Tall buildings in cold climates experience severe stack effect. The extra amount of heat provided by the air-conditioning system in attempts to overcome this problem can be substantial. The following features help combat infiltration from stack effect:

- Revolving doors or vestibules at exterior entrances
- Pressurized lobbies or lower floors
- Tight gaskets on stairwell doors leading to the roof
- Automatic dampers on elevator shaft vents
- Tight construction of the exterior skin
- Tight closure and seals on all dampers opening to the exterior

BOWLING CENTERS

Bowling centers may also contain a bar, a restaurant, a children's play area, offices, locker rooms, and other types of facilities. These auxiliary areas are not discussed in this section, except as they may affect design for the bowling area, which consists of alleys and a spectator area.

Load Characteristics

Bowling alleys usually have their peak use in the evenings, but weekend daytime use may also be heavy. Thus, when designing for the building's peak air-conditioning load, it is necessary to compare the day load and its high outside solar load and off-peak people load with the evening peak people load and zero solar load. Because bowling areas generally have little fenestration, solar load may not be important.

If the building contains auxiliary areas, these areas may be included in the refrigeration, heating, and air distribution systems for the bowling alleys, with suitable provisions for zoning the different areas as dictated by load analysis. Alternatively, separate systems may be established for each area with different load operation characteristics.

Heat build-up from lights, external transmission load, and pin-setting machinery in front of the foul line can be reduced by exhausting some air above the alleys or from the area containing the pin-setting machines; however, this gain should be compared against the cost of conditioning additional makeup air. In calculating the air-conditioning load, a portion of the unoccupied alley space load is included. Because this consists mainly of lights and some transmission load, about 15 to 30% of this heat load may have to be taken into account. The higher figure may apply when the roof is poorly insulated, no exhaust air is taken from this area, or no vertical baffle is used at the foul line. One estimate is 5 to 10 Btu/h per square foot of vertical surface at the foul line, depending mostly on the type and intensity of the lighting.

The heat load from bowlers and spectators may be found in Table 1 in Chapter 30 of the 2005 *ASHRAE Handbook—Fundamentals.* The proper heat gain should be applied for each person to avoid too large a design heat load.

Design Concepts

As with other building types having high occupancy loads, heavy smoke and odor concentration, and low sensible heat factors, all-air systems are generally the most suitable for bowling alley areas. Because most bowling alleys are almost windowless except for areas such as entrances, exterior restaurants, and bars, it is uneconomical to use terminal unit systems because of the small number required. Where required, radiation in the form of baseboard or radiant ceiling panels is generally placed at perimeter walls and entrances.

It is not necessary to maintain normal inside temperatures down the length of the alleys; temperatures may be graded down to the pin area. Unit heaters are often used at this location.

Air Pressurization. Spectator and bowling areas must be well shielded from entrances so that no cold drafts are created in these areas. To minimize infiltration of outside air into the alleys, the exhaust and return air system should handle only 85 to 90% of the total supply air, maintaining a positive pressure in the space when outside air pressurization is taken into consideration.

Air Distribution. Packaged units without ductwork produce uneven space temperatures and, unless they are carefully located and installed, may cause objectionable drafts. Central ductwork is recommended for all but the smallest buildings, even where packaged refrigeration units are used. Because only the areas behind the foul line are air conditioned, the ductwork should provide comfortable conditions within this area.

The return and exhaust air systems should have a large number of small registers uniformly located at high points, or pockets, to draw off the hot, smoky, and odorous air. In some parts of the country and for larger bowling alleys, it may be desirable to use all outside air to cool during intermediate seasons.

Special Considerations

People in sports and amusement centers engage in a high degree of physical activity, which makes them feel warmer and increases their rate of evaporation. In these places, odor and smoke control are important environmental considerations.

Bowling centers are characterized by the following:

- A large number of people concentrated in a relatively small area of a very large room. A major portion of the floor area is unoccupied.
- Heavy smoking, high physical activity, and high latent heat load.
- Greatest use from about 6:00 PM to midnight.

The first two items make furnishing large amounts of outside air mandatory to minimize odors and smoke in the atmosphere.

The area between the foul line and bowling pins need not be air conditioned or ventilated. Transparent or opaque vertical partitions are sometimes installed to separate the upper portions of the occupied and unoccupied areas so that air distribution is better contained within the occupied area.

COMMUNICATIONS CENTERS

Communication centers include telephone terminal buildings, radio stations, television studios, and transmitter and receiver

stations. Most telephone terminal rooms are air conditioned because constant temperature and relative humidity help prevent breakdowns and increase equipment life. In addition, air conditioning allows the use of a lower number of air changes, which, for a given filter efficiency, decreases the chances of damage to relay contacts and other delicate equipment.

Radio and television studios require critical analysis to eliminate heat build-up and control noise. Television studios have the added problem of air movement, lighting, and occupancy load variations. This section deals with television studios because they present most of the problems also found in radio studios.

Load Characteristics

Human occupancy is limited in telephone terminal rooms, so the air-conditioning load is primarily equipment heat load.

Television studios have very high lighting capacities, and the lighting load intensity may fluctuate considerably over short periods. Operating hours may vary every day. In addition, there may be from one to several dozen people onstage for short times. The air-conditioning system must be extremely flexible and able to handle wide load variations quickly, accurately, and efficiently, similar to the conditions of a theater stage. The studio may also have an assembly area with a large number of spectator seats. Generally, studios are located so that they are completely shielded from external noise and thermal environments.

Design Concepts

The critical areas of a television studio are the performance studio and control rooms. The audience area may be treated much like a place of assembly (see Chapter 4 for more information). Each area should have its own air distribution system or at least its own zone control separate from the studio system. Heat generated in the studio area should not be allowed to permeate the audience atmosphere.

The air distribution system selected must have the capabilities of a dual-duct, single-duct system with cooling and heating booster coils, a variable-air-volume system, or a multizone system to satisfy design criteria. The air distribution system should be designed so that simultaneous heating and cooling cannot occur unless heating is achieved solely by heat recovery.

Studio loads seldom exceed 100 tons of refrigeration. Even if it is part of a large communications center or building, the studio should have its own refrigeration system in case of emergencies. The refrigeration equipment in this size range may be reciprocating units, which require a remote location so that machine noise is isolated from the studio.

Special Considerations

On-Camera Studio. This is the "stage" of the television studio and requires the same general considerations as a concert hall stage. Air movement must be uniform, and, because scenery, cameras, and equipment may be moved during the performance, ductwork must be planned carefully to avoid interference with proper studio operation.

Control Room. Each studio may have one or more control rooms serving different functions. The video control room, which is occupied by the program and technical directors, contains monitors and picture-effect controls and may require up to 30 air changes per hour to maintain proper conditions. The large number of necessary air changes and the low sound level that must be maintained require special analysis of the air distribution system.

If a separate control room is furnished for the announcer, its heat load and air distribution problems will not be as critical as those for control rooms for the program, technical, and audio directors.

Thermostatic control should be furnished in each control room, and provisions should be made to allow occupants to turn the air conditioning on and off.

Noise Control. Studio microphones are moved throughout the studio during a performance, and they may be moved past or set near air outlets or returns. These microphones are considerably more sensitive than the human ear; therefore, air outlets or returns should be located away from areas where microphones are likely to be used. Even a leaky pneumatic thermostat can be a problem.

Air Distribution. Ductwork must be fabricated and installed so that there are no rough edges, poor turns, or improperly installed dampers to cause turbulence and eddy currents in the ducts. Ductwork should contain no holes or openings that might create whistles. Air outlet locations and the distribution pattern must be carefully analyzed to eliminate turbulence and eddy currents in the studio that might cause noise that could be picked up by studio microphones.

At least some portions of supply, return, and exhaust ductwork require acoustical material to maintain noise criterion (NC) levels from 20 to 25. Any duct serving more than one room should acoustically separate each room with a sound trap. All ductwork should be suspended by means of neoprene or rubber in shear-type vibration mountings. Where ductwork goes through wall or floor slabs, the openings should be sealed with acoustically deadening material. The supply fan discharge and return and exhaust fan inlets should have sound traps; all ductwork connections to fans should be made with nonmetallic, flexible material. Air outlet locations should be coordinated with ceiling-mounted tracks and equipment. Air distribution for control rooms may require a perforated ceiling outlet or return air plenum system.

Piping Distribution. All piping in the studio, as well as in adjacent areas that might transmit noise to the studio, should be supported by suitable vibration isolation hangers. To prevent transmitting vibration, piping should be supported from rigid structural elements to maximize absorption.

Mechanical Equipment Room. This room should be located as far from the studio as possible. All equipment should be selected for very quiet operation and should be mounted on suitable vibration-eliminating supports. Structural separation of the room from the studio is generally required.

See Chapter 47 for more information on sound and vibration control.

Air Movement. It is essential that air movement in the stage area, which often contains scenery and people, be kept below 25 fpm within 12 ft of the floor. The scenery is often fragile and will move in air velocities above 25 fpm; also, actors' hair and clothing may be disturbed.

Offices and Dressing Rooms. The functions of these rooms are quite different from each other and from the studio areas. It is recommended that such rooms be treated as separate zones, with their own controls.

Air Return. Whenever practicable, the largest portion of studio air should be returned over the banks of lights. This is similar to theater stage practice. Sufficient air should also be removed from studio high points to prevent heat build-up.

TRANSPORTATION CENTERS

The major transportation facilities are airports, ship docks, bus terminals, and passenger car garages. Airplane hangars and freight and mail buildings are also among the types of buildings to be considered. Freight and mail buildings are usually handled as standard warehouses.

Load Characteristics

Airports, ship docks, and bus terminals operate on a 24 h basis, with a reduced schedule during late night and early morning hours.

Airports. Terminal buildings consist of large, open circulating areas, one or more floors high, often with high ceilings, ticketing counters, and various types of stores, concessions, and convenience facilities. Lighting and equipment loads are generally average, but

occupancy varies substantially. Exterior loads are, of course, a function of architectural design. The largest single problem often is thermal drafts created by large entranceways, high ceilings, and long passageways, which have many openings to the outside.

Ship Docks. Freight and passenger docks consist of large, high-ceilinged structures with separate areas for administration, visitors, passengers, cargo storage, and work. The floor of the dock is usually exposed to the outside just above the water level. Portions of the side walls are often open while ships are in port. In addition, the large ceiling (roof) area presents a large heating and cooling load. Load characteristics of passenger dock terminals generally require roof and floors to be well insulated. Occasional heavy occupancy loads in visitor and passenger areas must be considered.

Bus Terminals. This building type consists of two general areas: the terminal building, which contains passenger circulation, ticket booths, and stores or concessions, and the bus loading area. Waiting rooms and passenger concourse areas are subject to a highly variable people load. Occupancy density may reach 10 ft^2 per person and, at extreme periods, 3 to 5 ft^2 per person. Chapter 13 has further information on bus terminals.

Design Concepts

Heating and cooling is generally centralized or provided for each building or group in a complex. In large, open-circulation areas of transportation centers, any all-air system with zone control can be used. Where ceilings are high, air distribution is often along the side wall to concentrate air conditioning where desired and avoid disturbing stratified air. Perimeter areas may require heating by radiation, a fan-coil system, or hot air blown up from the sill or floor grilles, particularly in colder climates. Hydronic perimeter radiant ceiling panels may be especially suited to these high-load areas.

Airports. Airports generally consist of one or more central terminal buildings connected by long passageways or trains to rotundas containing departure lounges for airplane loading. Most terminals have portable telescoping-type loading bridges connecting departure lounges to the airplanes. These passageways eliminate heating and cooling problems associated with traditional permanent structure passenger loading.

Because of difficulties in controlling the air balance because of the many outside openings, high ceilings, and long, low passageways (which often are not air conditioned), the terminal building (usually air conditioned) should be designed to maintain a substantial positive pressure. Zoning is generally required in passenger waiting areas, in departure lounges, and at ticket counters to take care of the widely variable occupancy loads.

Main entrances may have vestibules and windbreaker partitions to minimize undesirable air currents in the building.

Hangars must be heated in cold weather, and ventilation may be required to eliminate possible fumes (although fueling is seldom permitted in hangars). Gas-fired, electric, and low- and high-intensity radiant heaters are used extensively in hangars because they provide comfort for employees at relatively low operating costs.

Hangars may also be heated by large air blast heaters or floor-buried heated liquid coils. Local exhaust air systems may be used to evacuate fumes and odors that occur in smaller ducted systems. Under some conditions, exhaust systems may be portable and may include odor-absorbing devices.

Ship Docks. In severe climates, occupied floor areas may contain heated floor panels. The roof should be well insulated, and, in appropriate climates, evaporative spray cooling substantially reduces the summer load. Freight docks are usually heated and well ventilated but seldom cooled.

High ceilings and openings to the outside may present serious draft problems unless the systems are designed properly. Vestibule entrances or air curtains help minimize cross-drafts. Air door blast heaters at cargo opening areas may be quite effective.

Ventilation of the dock terminal should prevent noxious fumes and odors from reaching occupied areas. Therefore, occupied areas should be under positive pressure, and cargo and storage areas exhausted to maintain negative air pressure. Occupied areas should be enclosed to simplify any local air conditioning.

In many respects, these are among the most difficult buildings to heat and cool because of their large open areas. If each function is properly enclosed, any commonly used all-air or large fan-coil system is suitable. If areas are left largely open, the best approach is to concentrate on proper building design and heating and cooling of the openings. High-intensity infrared spot heating is often advantageous (see Chapter 15 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*). Exhaust ventilation from tow truck and cargo areas should be exhausted through the roof of the dock terminal.

Bus Terminals. Conditions are similar to those for airport terminals, except that all-air systems are more practical because ceiling heights are often lower, and perimeters are usually flanked by stores or office areas. The same systems are applicable as for airport terminals, but ceiling air distribution is generally feasible.

Properly designed radiant hydronic or electric ceiling systems may be used if high-occupancy latent loads are fully considered. This may result in smaller duct sizes than are required for all-air systems and may be advantageous where bus loading areas are above the terminal and require structural beams. This heating and cooling system reduces the volume of the building that must be conditioned. In areas where latent load is a concern, heating-only panels may be used at the perimeter, with a cooling-only interior system.

The terminal area air supply system should be under high positive pressure to ensure that no fumes and odors infiltrate from bus areas. Positive exhaust from bus loading areas is essential for a properly operating total system (see Chapter 13).

Special Considerations

Airports. Filtering outside air with activated charcoal filters should be considered for areas subject to excessive noxious fumes from jet engine exhausts. However, locating outside air intakes as remotely as possible from airplanes is a less expensive and more positive approach.

Where ionization filtration enhancers are used, outside air quantities are sometimes reduced because of cleaner air. However, care must be taken to maintain sufficient amounts of outside air for space pressurization.

Ship Docks. Ventilation design must ensure that fumes and odors from forklifts and cargo in work areas do not penetrate occupied and administrative areas.

Bus Terminals. The primary concerns with enclosed bus loading areas are health and safety problems, which must be handled by proper ventilation (see Chapter 13). Although diesel engine fumes are generally not as noxious as gasoline fumes, bus terminals often have many buses loading and unloading at the same time, and the total amount of fumes and odors may be disturbing.

Enclosed Garages. In terms of health and safety, enclosed bus loading areas and automobile parking garages present the most serious problems in these buildings. Three major problems are encountered. The first and most serious is emission of carbon monoxide (CO) by cars and oxides of nitrogen by buses, which can cause serious illness and possibly death. The second problem is oil and gasoline fumes, which may cause nausea and headaches and can also create a fire hazard. The third is lack of air movement and the resulting stale atmosphere that develops because of increased carbon dioxide content in the air. This condition may cause headaches or grogginess. Most codes require a minimum ventilation rate to ensure that the CO concentration does not exceed safe limits. Chapter 13 covers ventilation requirements and calculation procedures for enclosed vehicular facilities in detail.

All underground garages should have facilities for testing the CO concentration or should have the garage checked periodically. Problems such as clogged duct systems; improperly operating fans, motors, or dampers; or clogged air intake or exhaust louvers, may not allow proper air circulation. Proper maintenance is required to minimize any operational defects.

WAREHOUSES

Warehouses are used to store merchandise and may be open to the public at times. They are also used to store equipment and material inventory at industrial facilities. The buildings are generally not air conditioned, but often have sufficient heat and ventilation to provide a tolerable working environment. Associated facilities occupied by office workers, such as shipping, receiving, and inventory control offices, are generally air conditioned.

Load Characteristics

Internal loads from lighting, people, and miscellaneous sources are generally low. Most of the load is thermal transmission and infiltration. An air-conditioning load profile tends to flatten where materials stored are massive enough to cause the peak load to lag.

Design Concepts

Most warehouses are only heated and ventilated. Forced-flow unit heaters may be located near heat entrances and work areas. Large central heating and ventilating units are widely used. Even though comfort for warehouse workers may not be considered, it may be necessary to keep the temperature above 40°F to protect sprinkler piping or stored materials from freezing.

A building designed for the addition of air conditioning at a later date will require less heating and be more comfortable. For maximum summer comfort without air conditioning, excellent ventilation with noticeable air movement in work areas is necessary. Even greater comfort can be achieved in appropriate climates by adding roof spray cooling. This can reduce the roof's surface temperature by 40 to 60°F, thereby reducing ceiling radiation inside. Low- and high-intensity radiant heaters can be used to maintain the minimum ambient temperature throughout a facility above freezing. Radiant heat may also be used for occupant comfort in areas permanently or frequently open to the outside.

If the stored product requires defined inside conditions, an air-conditioning system must be added. Using only ventilation may help maintain lower space temperatures, but care should be taken not to damage the stored product with uncontrolled humidity. Direct or indirect evaporative cooling may also be an option.

Special Considerations

Forklifts and trucks powered by gasoline, propane, and other fuels are often used inside warehouses. Proper ventilation is necessary to alleviate build-up of CO and other noxious fumes. Proper ventilation of battery-charging rooms for electrically powered forklifts and trucks is also required.

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CHAPTER 4

PLACES OF ASSEMBLY

ASSEMBLY rooms are generally large, have relatively high ceilings, and are few in number for any given facility. They usually have a periodically high density of occupancy per unit floor area, as compared to other buildings, and thus have a relatively low design sensible heat ratio.

This chapter summarizes some of the design concerns for enclosed assembly buildings. (Chapter 3, which covers general criteria for commercial and public buildings, also includes information that applies to public assembly buildings.)

GENERAL CRITERIA

Energy conservation codes and standards must be considered because they have a major impact on design and performance.

Assembly buildings may have relatively few hours of use per week and may not be in full use when maximum outdoor temperatures or solar loading occur. Often they are fully occupied for as little as 1 to 2 h, and the load may be materially reduced by precooling. The designer needs to obtain as much information as possible about the anticipated hours of use, particularly times of full seating, so that simultaneous loads may be considered to optimize performance and operating economy. Dehumidification requirements should be considered before reducing equipment size. The intermittent or infrequent nature of the cooling loads may allow these buildings to benefit from thermal storage systems.

Occupants usually generate the major room cooling and ventilation load. The number of occupants is best determined from the seat count, but when this is not available, it can be estimated at 7.5 to 10 ft^2 per person for the entire seating area, including exit aisles but not the stage, performance areas, or entrance lobbies.

Safety and Security

Assembly buildings may need new safety and security considerations regarding extraordinary incidents. Designers should follow the recommendations outlined in Chapter 58.

Outdoor Air

Outdoor air ventilation rates as prescribed by ASHRAE *Standard* 62.1 can be a major portion of the total load. The latent load (dehumidification and humidification) and energy used to maintain relative humidity within prescribed limits are also concerns. Humidity must be maintained at proper levels to prevent mold and mildew growth and for acceptable indoor air quality and comfort.

Lighting Loads

Lighting loads are one of the few major loads that vary from one type of assembly building to another. Levels can vary from 150 footcandles in convention halls where television cameras are expected to be used, to virtually nothing, as in a movie theater. In many assembly buildings, lights are controlled by dimmers or other means to present a suitably low level of light during performances,

with much higher lighting levels during cleanup, when the house is nearly empty. The designer should ascertain the light levels associated with maximum occupancies, not only for economy but also to determine the proper room sensible heat ratio.

Indoor Air Conditions

Indoor air temperature and humidity should follow ASHRAE comfort recommendations in Chapter 8 of the 2005 *ASHRAE Handbook—Fundamentals* and ASHRAE *Standard* 55. In addition, the following should be considered:

- In arenas, stadiums, gymnasiums, and movie theaters, people generally dress informally. Summer indoor conditions may favor the warmer end of the thermal comfort scale, and the winter indoor temperature may favor the cooler end.
- In churches, concert halls, and theaters, most men wear jackets and ties and women often wear suits. The temperature should favor the middle range of design, and there should be little summer-to-winter variation.
- In convention and exhibition centers, the public is continually walking. The indoor temperature should favor the lower range of comfort conditions both in summer and in winter.
- In spaces with a high population density or with a sensible heat factor of 0.75 or less, reheat should be considered.
- Energy conservation codes must be considered in both the design and during operation.

Assembly areas generally require some reheat to maintain the relative humidity at a suitably low level during periods of maximum occupancy. Refrigerant hot gas or condenser water is well suited for this purpose. Face-and-bypass control of low-temperature cooling coils is also effective. In colder climates, it may also be desirable to provide humidification. High rates of internal gain may make evaporative humidification attractive during economizer cooling.

Filtration

Most places of assembly are minimally filtered with filters rated at 30 to 35% efficiency, as tested in accordance with ASHRAE *Standard* 52.1. Where smoking is permitted, however, filters with a minimum rating of 80% are required to remove tobacco smoke effectively. Filters with 80% or higher efficiency are also recommended for facilities having particularly expensive interior decor. Because of the few operating hours of these facilities, the added expense of higher-efficiency filters can be justified by their longer life. Low-efficiency prefilters are generally used with high-efficiency filters to extend their useful life. Ionization and chemically reactive filters should be considered where high concentrations of smoke or odors are present.

Noise and Vibration Control

The desired noise criteria (NC) vary with the type and quality of the facility. The need for noise control may be minimal in a gymnasium or natatorium, but it is important in a concert hall. Multipurpose facilities require noise control evaluation over the entire spectrum of use.

The preparation of this chapter is assigned to TC 9.8, Large Building Air-Conditioning Applications.

In most cases, sound and vibration control is required for both equipment and duct systems, as well as in diffuser and grille selection. When designing a performance theater or concert hall, an experienced acoustics engineer should be consulted, because the quantity and quality or characteristic of the noise is very important.

Transmission of vibration and noise can be decreased by mounting pipes, ducts, and equipment on a separate structure independent of the music hall. If the mechanical equipment space is close to the music hall, the entire mechanical equipment room may need to be floated on isolators, including the floor slab, structural floor members, and other structural elements such as supporting pipes or similar materials that can carry vibrations. Properly designed inertia pads are often used under each piece of equipment. The equipment is then mounted on vibration isolators.

Manufacturers of vibration isolating equipment have devised methods to float large rooms and entire buildings on isolators. Where subway and street noise may be carried into the structure of a music hall, it is necessary to float the entire music hall on isolators. If the music hall is isolated from outside noise and vibration, it also must be isolated from mechanical equipment and other internal noise and vibrations.

External noise from mechanical equipment such as cooling towers should not enter the building. Avoid designs that allow noises to enter the space through air intakes or reliefs and carelessly designed duct systems.

For more details on noise and vibration control, see Chapter 47 of this volume and Chapter 7 in the 2005 *ASHRAE Handbook—Fundamentals*.

Ancillary Facilities

Ancillary facilities are generally a part of any assembly building; almost all have some office space. Convention centers and many auditoriums, arenas, and stadiums have restaurants and cocktail lounges. Churches may have apartments for clergy or a school. Many facilities have parking structures. These varied ancillary facilities are discussed in other chapters of this volume. However, for reasonable operating economy, these facilities should be served by separate systems when their hours of use differ from those of the main assembly areas.

Air Conditioning

Because of their characteristic large size and need for considerable ventilation air, assembly buildings are frequently served by single-zone or variable-volume systems providing 100% outdoor air. Separate air-handling units usually serve each zone, although multizone, dual-duct, or reheat types can also be applied with lower operating efficiency. In larger facilities, separate zones are generally provided for entrance lobbies and arterial corridors that surround the seating space. Low-intensity radiant heating is often an efficient alternative. In some assembly rooms, folding or rolling partitions divide the space for different functions, so a separate zone of control for each resultant space is best. In extremely large facilities, several air-handling systems may serve a single space, because of the limits of equipment size and also for energy and demand considerations.

Peak Load Reduction

There are several techniques currently in use to help address peak loads. **Thermal storage** is discussed in Chapter 34. Another popular technique, **precooling**, can be managed by the building operator. Precooling the building mass several degrees below the desired indoor temperature several hours before it is occupied allows it to absorb a part of the peak heat load. This cooling reduces the equipment size needed to meet short-term loads. The effect can be used if cooling time of at least 1 h is available prior to occupancy, and then only when the period of peak load is relatively short (2 h or less).

The designer must advise the owner that the space temperature will be cold to most people as occupancy begins, but will warm up as the performance progresses; this should be understood by all concerned before proceeding with precooling. Precooling works best when the space is used only occasionally during the hotter part of the day and when provision of full capacity for an occasional purpose is not economically justifiable.

Stratification

Because most assembly buildings have relatively high ceilings, some heat may be allowed to stratify above the occupied zone, thereby reducing load on the equipment. Heat from lights can be stratified, except for the radiant portion (about 50% for fluorescent and 65% for incandescent or mercury-vapor fixtures). Similarly, only the radiant effect of the upper wall and roof load (about 33%) reaches the occupied space. Stratification only occurs when air is admitted and returned at a sufficiently low elevation so that it does not mix with the upper air. Conversely, stratification may increase heating loads during periods of minimal occupancy in winter. In these cases, ceiling fans, air-handling systems, or high/low air distribution may be desirable to reduce stratification. Balconies may also be affected by stratification and should be well ventilated.

Air Distribution

In assembly buildings with seating, people generally remain in one place throughout a performance, so they cannot move away from drafts. Therefore, good air distribution is essential. Airflow-modeling software could prove helpful in predicting potential problem areas.

Heating is seldom a major problem, except at entrances or during warm-up before occupancy. Generally, the seating area is isolated from the exterior by lobbies, corridors, and other ancillary spaces. For cooling, air can be supplied from the overhead space, where it mixes with heat from the lights and occupants. Return air openings can also aid air distribution. Air returns located below seating or at a low level around the seating can effectively distribute air with minimum drafts; however, register velocities over 275 fpm may cause objectionable drafts and noise.

Because of the configuration of these spaces, supply jet nozzles with long throws of 50 to 150 ft may need to be installed on sidewalls. For ceiling distribution, downward throw is not critical if returns are low. This approach has been successful in applications that are not particularly noise-sensitive, but the designer needs to select air distribution nozzles carefully.

The air-conditioning systems must be quiet. This is difficult to achieve if supply air is expected to travel 30 ft or more from sidewall outlets to condition the center of the seating area. Because most houses of worship, theaters, and halls are large, high air discharge velocities from the wall outlets are required. These high velocities can produce objectionable noise levels for people sitting near the outlets. This can be avoided if the return air system does some of the work. The supply air must be discharged from the air outlet (preferably at the ceiling) at the highest velocity consistent with an acceptable noise level. Although this velocity does not allow the conditioned air to reach all seats, the return air registers, which are located near seats not reached by the conditioned air, pull the air to cool or heat the audience, as required. In this way, supply air blankets the seating area and is pulled down uniformly by return air registers under or beside the seats.

A certain amount of exhaust air should be taken from the ceiling of the seating area, preferably over the balcony (if there is one) to prevent pockets of hot air, which can produce a radiant effect and cause discomfort, as well as increase the cost of air conditioning. Where the ceiling is close to the audience (e.g., below balconies and mezzanines), specially designed plaques or air-distributing ceilings should be provided to absorb noise.

Regular ceiling diffusers placed more than 30 ft apart normally give acceptable results if careful engineering is applied in selecting

the diffusers. Because large air quantities are generally involved and because the building is large, fairly large capacity diffusers, which tend to be noisy, are frequently selected. Linear diffusers are more acceptable architecturally and perform well if selected properly. Integral dampers in diffusers should not be used as the only means of balancing because they generate intolerable amounts of noise, particularly in larger diffusers.

Mechanical Equipment Rooms

The location of mechanical and electrical equipment rooms affects the degree of sound attenuation treatment required. Those located near the seating area are more critical because of the normal attenuation of sound through space. Those near the stage area are critical because the stage is designed to project sound to the audience. If possible, mechanical equipment rooms should be in an area separated from the main seating or stage area by buffers such as lobbies or service areas. The economies of the structure, attenuation, equipment logistics, and site must be considered in selecting locations for mechanical equipment rooms.

At least one mechanical equipment room is placed near the roof to house the toilet exhaust, general exhaust, cooling tower, kitchen, and emergency stage exhaust fans, if any. Individual roof-mounted exhaust fans may be used, thus eliminating the need for a mechanical equipment room. However, to reduce sound problems, mechanical equipment should not be located on the roof over the music hall or stage but rather over offices, storerooms, or auxiliary areas.

HOUSES OF WORSHIP

Houses of worship seldom have full or near-full occupancy more than once a week, but they have considerable use for smaller functions (meetings, weddings, funerals, christenings, or daycare) throughout the rest of the week. It is important to determine how and when the building will be used. When thermal storage is used, longer operation of equipment before occupancy may be required because of the structure's high thermal mass. Seating capacity is usually well defined. Some houses of worship have a movable partition to form a single large auditorium for special holiday services. It is important to know how often this maximum use is expected.

Houses of worship test a designer's ingenuity in locating equipment and air diffusion devices in architecturally acceptable places. Because occupants are often seated, drafts and cold floors should be avoided. Many houses of worship have high, vaulted ceilings, which create thermal stratification. Where stained glass is used, a shade coefficient equal to solar glass (SC = 0.70) is assumed.

Houses of worship may also have auxiliary rooms that should be air conditioned. To ensure privacy, sound transmission between adjacent areas should be considered in the air distribution scheme. Diversity in the total air-conditioning load requirements should be evaluated to take full advantage of the characteristics of each area.

It is desirable to provide some degree of individual control for the platform, sacristy, and bema or choir area.

AUDITORIUMS

The types of auditoriums considered are movie theaters, playhouses, and concert halls. Auditoriums in schools and the large auditoriums in some convention centers may follow the same principles, with varying degrees of complexity.

Movie Theaters

Motion picture theaters are the simplest of the auditorium structures discussed here. They run continuously for periods of 8 h or more and, thus, are not a good choice for precooling techniques, except for the first matinee peak. They operate frequently at low occupancy levels, and low-load performance must be considered. Additionally, they tend to have lower sensible heat factors; special

care must be taken to ensure proper relative humidity levels can be maintained without overcooling the space.

Motion picture sound systems make noise control less important than it is in other kinds of theaters. The lobby and exit passageways in a motion picture theater are seldom densely occupied, although some light to moderate congestion can be expected for short times in the lobby area. A reasonable design for the lobby space is one person per 20 to 30 ft^2.

Lights are usually dimmed when the house is occupied; full lighting intensity is used only during cleaning. A reasonable value for lamps above the seating area during a performance is 5 to 10% of the installed wattage. Designated smoking areas should be handled with separate exhaust or air-handling systems to avoid contamination of the entire facility.

Projection Booths. The projection booth represents a larger challenge in movie theater design. For large theaters using high-intensity lamps, projection room design must follow applicable building codes. If no building code applies, the projection equipment manufacturer usually has specific requirements. The projection room may be air conditioned, but it is normally exhausted or operated at negative pressure. Exhaust is normally taken through the housing of the projectors. Additional exhaust is required for the projectionist's sanitary facilities. Other heat sources include sound and dimming equipment, which require a continuously controlled environment and necessitate a separate system.

Smaller theaters have fewer requirements for projection booths. It is a good idea to condition the projection room with filtered supply air to avoid soiling lenses. In addition to the projector light, heat sources in the projection room include the sound equipment, as well as the dimming equipment.

Performance Theaters

Performance theaters differ from motion picture theaters in the following ways:

- Performances are seldom continuous. Where more than one performance occurs in a day, performances are usually separated by 2 to 4 h. Accordingly, precooling techniques are applicable, particularly for afternoon performances.
- Performance theaters generally play to a full or near-full house.
- Performance theaters usually have intermissions, and the lobby areas are used for drinking and socializing. The intermissions are usually relatively short, seldom exceeding 15 to 20 min; however, the load may be as dense as one person per 5 ft^2.
- Because sound amplification is less used than in motion picture theaters, background noise control is more important.
- Stage lighting contributes considerably to the total cooling load in performance theaters. Lighting loads can vary from performance to performance.

Stages. The stage presents the most complex problem. It consists of the following loads:

- A heavy, mobile lighting load
- Intricate or delicate stage scenery, which varies from scene to scene and presents difficult air distribution requirements
- Actors, who may perform tasks that require exertion

Approximately 40 to 60% of the lighting load can be eliminated by exhausting air around the lights. This procedure works for lights around the proscenium. However, it is more difficult to place exhaust air ducts directly above lights over the stage because of the scenery and light drops. Careful coordination is required to achieve an effective and flexible layout.

Conditioned air should be introduced from the low side and back stages and returned or exhausted around the lights. Some exhaust air must be taken from the top of the tower directly over the stage containing lights and equipment (i.e., the fly). Air distribution design is further complicated because pieces of scenery may consist of light

materials that flutter in the slightest air current. Even the vertical stack effect created by the heat from lights may cause this motion. Therefore, low air velocities are essential and air must be distributed over a wide area with numerous supply and return registers.

With multiple scenery changes, low supply or return registers from the floor of the stage are almost impossible to provide. However, some return air at the footlights and for the prompter should be considered. Air conditioning should also be provided for the stage manager and control board areas.

In many theaters with overhead flies, the stage curtain billows when it is down. This is primarily caused by the stack effect created by the height of the main stage tower, heat from lights, and the temperature difference between the stage and seating areas. Proper air distribution and balancing can minimize this phenomenon. Bypass damper arrangements with suitable fire protection devices may be feasible.

Loading docks adjacent to stages located in cold climates should be heated. Doors to these areas may be open for long periods, for example, while scenery is being loaded or unloaded for a performance.

On the stage, local code requirements must be followed for emergency exhaust ductwork or skylight (or blow-out hatch) requirements. These openings are often sizable and should be incorporated in the early design concepts.

Concert Halls

Concert halls and music halls are similar to performance theaters. They normally have a full stage, complete with fly gallery, and dressing areas for performers. Generally, the only differences between the two are in size and decor, with the concert hall usually being larger and more elaborately decorated.

Air-conditioning design must consider that the concert hall is used frequently for special charity and civic events, which may be preceded or followed by parties (and may include dancing) in the lobby area. Concert halls often have cocktail lounge areas that become very crowded, with heavy smoking during intermissions. These areas should be equipped with flexible exhaust-recirculation systems. Concert halls may also have full restaurant facilities.

As in theatres, noise control is important. Design must avoid characterized or narrow-band noises in the level of audibility. Much of this noise is structure-borne, resulting from inadequate equipment and piping vibration isolation. An experienced acoustical engineer is essential for help in the design of these applications.

ARENAS AND STADIUMS

Functions at arenas and stadiums may be quite varied, so the air-conditioning loads will vary. Arenas and stadiums are not only used for sporting events such as basketball, ice hockey, boxing, and track meets but may also house circuses; rodeos; convocations; social affairs; meetings; rock concerts; car, cycle, and truck events; and special exhibitions such as home, industrial, animal, or sports shows. For multipurpose operations, the designer must provide highly flexible systems. High-volume ventilation may be satisfactory in many instances, depending on load characteristics and outside air conditions.

Load Characteristics

Depending on the range of use, the load may vary from a very low sensible heat ratio for events such as boxing to a relatively high sensible heat ratio for industrial exhibitions. Multispeed fans often improve performance at these two extremes and can aid in sound control for special events such as concerts or convocations. When using multispeed fans, the designer should consider the performance of the air distribution devices and cooling coils when the fan is operating at lower speeds.

Because total comfort cannot be ensured in an all-purpose facility, the designer must determine the level of discomfort that can be tolerated, or at least the type of performances for which the facility is primarily intended.

As with other assembly buildings, seating and lighting combinations are the most important load considerations. Boxing events, for example, may have the most seating, because the boxing ring area is very small. For the same reason, however, the area that needs to be intensely illuminated is also small. Thus, boxing matches may represent the largest latent load situation. Other events that present large latent loads are rock concerts and large-scale dinner dances, although the audience at a rock concert is generally less concerned with thermal comfort. Ventilation is also essential in removing smoke or fumes at car, cycle, and truck events. Circuses, basketball, and hockey have a much larger arena area and less seating. The sensible load from lighting the arena area improves the sensible heat ratio. The large expanse of ice in hockey games considerably reduces both latent and sensible loads. High latent loads caused by occupancy or ventilation can create severe problems in ice arenas such as condensation on interior surfaces and fog. Special attention should be paid to the ventilation system, air distribution, humidity control, and construction materials.

Enclosed Stadiums

An enclosed stadium may have either a retractable or a fixed roof. When the roof is closed, ventilation is needed, so ductwork must be run in the permanent sections of the stadium. The large air volumes and long air throws required make proper air distribution difficult to achieve; thus, the distribution system must be very flexible and adjustable.

Some open stadiums have radiant heating coils in the floor slabs of the seating areas. Gas-fired or electric high- or low-intensity radiant heating located above the occupants is also used.

Open racetrack stadiums may present a ventilation problem if the grandstand is enclosed. The grandstand area may have multiple levels and be in the range of 1300 ft long and 200 ft deep. The interior (ancillary) areas must be ventilated to control odors from toilet facilities, concessions, and the high population density. General practice provides about four air changes per hour for the stand seating area and exhausts air through the rear of the service areas. More efficient ventilation systems may be selected if architectural considerations allow. Window fogging is a winter concern with glass-enclosed grandstands. This can be minimized by double glazing, humidity control, moving dry air across the glass, or a radiant heating system for perimeter glass areas.

Air-supported structures require continuous fan operation to maintain a properly inflated condition. The possibility of condensation on the underside of the air bubble should be considered. The U-factor of the roof should be sufficient to prevent condensation at the lowest expected ambient temperature. Heating and air-conditioning functions can be either incorporated into the inflating system or furnished separately. Solar and radiation control is also possible through the structure's skin. Applications, though increasing rapidly, still require working closely with the enclosure manufacturer to achieve proper and integrated results.

Ancillary Spaces

The concourse areas of arenas and stadiums are heavily populated during entrance, exit, and intermission periods. Considerable odor is generated in these areas by food, drink, and smoke, requiring considerable ventilation. If energy conservation is an important factor, carbon filters and controllable recirculation rates should be considered. Concourse area air systems should be considered for their flexibility of returning or exhausting air. The economics of this type of flexibility should be evaluated with regard to the associated problem of air balance and freeze-up in cold climates.

Ticket offices, restaurants, and similar facilities are often expected to be open during hours that the main arena is closed; therefore, separate systems should be considered for these areas.

Locker rooms require little treatment other than excellent ventilation, usually not less than 2 or 3 cfm per square foot. To reduce the outdoor air load, excess air from the main arena or stadium may be transferred into the locker rooms. However, reheat or recooling by water or primary air should be considered to maintain the locker room temperature. To maintain proper air balance under all conditions, locker rooms should have separate supply and exhaust systems.

Ice Rinks

Refer to Chapter 35 of the 2006 *ASHRAE Handbook—Refrigeration* for ice sheet design information. When an ice rink is designed into the facility, the concerns of groundwater conditions, site drainage, structural foundations, insulation, and waterproofing become even more important, with the potential of freezing soil or fill under the floor and subsequent expansion. The rink floor may have to be strong enough to support heavy trucks. The floor insulation also must be strong enough to take this load. Ice-melting pits of sufficient size with steam pipes may have to be furnished. If the arena is to be air conditioned, the possibility of combining the air-conditioning system with the ice rink system could be considered. The designer should be aware, however, that both systems operate at vastly different temperatures and have considerably different operation profiles. The radiant effects of the ice on the people and of heat from the roof and lights on the ice must be considered in the design and operation of the system. Low air velocities at the ice sheet level help minimize the refrigeration load. Conversely, high air velocities cause the ice to melt or sublimate.

Fog forms when moisture-laden air cools below its dew point. This is most likely to occur close to the ice surface within the boarded area (playing area). Fog can be controlled by reducing the indoor dew point with a dehumidification system or high-latent-capacity air-conditioning system and by delivering appropriate air velocities to bring the air in contact with the ice. Air-conditioning systems have had limited success in reducing the dew-point temperature sufficiently to prevent fog. The section on Ice Rink Dehumidifiers in Chapter 47 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment* has more information on fog control.

The type of lighting used over ice rinks must be carefully considered when precooling is used before hockey games and between periods. Main lights should be able to be turned off, if feasible. Incandescent lights require no warm-up time and are more applicable than types requiring warm-up. Low-emissivity ceilings with reflective characteristics successfully reduce condensation on roof structures; they also reduce lighting and, consequently, the cooling requirements.

Gymnasiums

Smaller gymnasiums, such as those in schools, are miniature versions of arenas and often have multipurpose features. For further information, see Chapter 6, Educational Facilities.

Many school gymnasiums are not air conditioned. Low-intensity perimeter radiant heaters with central ventilation supplying four to six air changes per hour are effective and energy efficient. Unit heaters on the ceiling are also effective. Ventilation must be provided because of high activity levels and resulting odors.

Most gymnasiums are located in schools. However, public and private organizations and health centers may also have gymnasiums. During the day, gymnasiums are usually used for physical activities, but in the evening and on weekends, they may be used for sports events, social affairs, or meetings. Thus, their activities fall within the scope of those of a civic center. More gymnasiums are being considered for air conditioning to make them more suitable for civic center activities. Design criteria are similar to arenas and civic centers when used for such activities. However, for schooltime use, space temperatures are often kept between 65 and 68°F during the heating season. Occupancy and the degree of activity during daytime use does not usually require high quantities of outdoor air, but if used for other functions, system flexibility is required.

CONVENTION AND EXHIBITION CENTERS

Convention and exhibition centers schedule diverse functions similar to those at arenas and stadiums and present a unique challenge to the designer. The center generally is a high-bay, long-span space, and can change weekly, for example, from an enormous computer room into a gigantic kitchen, large machine shop, department store, automobile showroom, or miniature zoo. They can also be the site of gala banquets or used as major convention meeting rooms.

Income earned by these facilities is directly affected by the time it takes to change from one activity to the next, so highly flexible utility distribution and air-conditioning equipment are needed.

Ancillary facilities include restaurants, bars, concession stands, parking garages, offices, television broadcasting rooms, and multiple meeting rooms varying in capacity from small (10 to 20 people) to large (hundreds or thousands of people). Often, an appropriately sized full-scale auditorium or arena is also incorporated.

By their nature, these facilities are much too large and diverse in their use to be served by a single air-handling system. Multiple air handlers with several chillers can be economical.

Load Characteristics

The main exhibition room is subject to a variety of loads, depending on the type of activity in progress. Industrial shows provide the highest sensible loads, which may have a connected capacity of 20 W/ft^2 along with one person per 40 to 50 ft^2. Loads of this magnitude are seldom considered because large power-consuming equipment is seldom in continuous operation at full load. An adequate design accommodates (in addition to lighting load) about 10 W/ft^2 and one person per 40 to 50 ft^2 as a maximum continuous load.

Alternative loads of very different character may be encountered. When the main hall is used as a meeting room, the load will be much more latent. Thus, multispeed fans or variable-volume systems may provide a better balance of load during these high-latent, low-sensible periods of use. Accurate occupancy and usage information is critical in any plan to design and operate such a facility efficiently and effectively.

System Applicability

The main exhibition hall is normally handled by one or more all-air systems. This equipment should be able to operate on all outdoor air, because during set-up, the hall may contain highway-size trucks bringing in or removing exhibit materials. There are also occasions when the space is used for equipment that produces an unusual amount of fumes or odors, such as restaurant or printing industry displays. It is helpful to build some flues into the structure to duct fumes directly to the outside. Perimeter radiant ceiling heaters have been successfully applied to exhibition halls with large expanses of glass.

Smaller meeting rooms are best conditioned either with individual room air handlers, or with variable-volume central systems, because these rooms have high individual peak loads but are not used frequently. Constant-volume systems of the dual- or single-duct reheat type waste considerable energy when serving empty rooms, unless special design features are incorporated.

Offices and restaurants often operate for many more hours than the meeting areas or exhibition areas and should be served separately. Storage areas can generally be conditioned by exhausting excess air from the main exhibit hall through these spaces.

NATATORIUMS

Environmental Control

A natatorium requires year-round humidity levels between 40 and 60% for comfort, energy consumption, and building protection. The designer must address the following concerns: humidity control, ventilation requirements for air quality (outdoor and exhaust air), air distribution, duct design, pool water chemistry, and evaporation rates. A humidity control system will not provide satisfactory results if any of these items are overlooked. See Chapter 47 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment* for additional dehumidifier application and design information.

Humidity Control

People are very sensitive to relative humidity. Fluctuations in relative humidity outside the 40 to 60% range can increase levels of bacteria, viruses, fungi and other factors that reduce air quality. For swimmers, 50 to 60% rh is most comfortable. High relative humidity levels are destructive to building components. Mold and mildew can attack wall, floor, and ceiling coverings, and condensation can degrade many building materials. In the worst case, the roof could collapse because of corrosion from water condensing on the structure.

Load Estimation

Loads for a natatorium include heat gains and losses from outdoor air, lighting, walls, roof, and glass. Internal latent loads are generally from people and evaporation. Evaporation loads in pools and spas are significant relative to other load elements and may vary widely depending on pool features, areas of water and wet deck, water temperature, and activity level in the pool.

Evaporation. The rate of evaporation can be estimated from empirical Equation (1). This equation is valid for pools at normal activity levels, allowing for splashing and a limited area of wetted deck. Other pool uses may have more or less evaporation (Smith et al. 1993).

$$w_p = \frac{A}{Y}(p_w - p_a)(95 + 0.425V) \qquad (1)$$

where

- w_p = evaporation of water, lb/h
- A = area of pool surface, ft^2
- Y = latent heat required to change water to vapor at surface water temperature, Btu/lb
- p_w = saturation vapor pressure taken at surface water temperature, in. Hg
- p_a = saturation pressure at room air dew point, in. Hg
- V = air velocity over water surface, fpm

The units for the constant 95 are Btu/(h·ft^2·in. Hg). The units for the constant 0.425 are Btu·min/(h·ft^3·in. Hg).

Equation (1) may be modified by multiplying it by an activity factor F_a to alter the estimate of evaporation rate based on the level of activity supported. For Y values of about 1000 Btu/lb and V values ranging from 10 to 30 fpm, Equation (1) can be reduced to

$$w_p = 0.1A(p_w - p_a)F_a \qquad (2)$$

Table 1   Typical Natatorium Design Conditions

Type of Pool	Air Temperature, °F	Water Temperature, °F	Relative Humidity, %
Recreational	75 to 85	75 to 85	50 to 60
Therapeutic	80 to 85	85 to 95	50 to 60
Competition	78 to 85	76 to 82	50 to 60
Diving	80 to 85	80 to 90	50 to 60
Elderly swimmers	84 to 90	85 to 90	50 to 60
Hotel	82 to 85	82 to 86	50 to 60
Whirlpool/spa	80 to 85	97 to 104	50 to 60

The following activity factors should be applied to the areas of specific features, and not to the entire wetted area:

Type of Pool	Typical Activity Factor (F_a)
Baseline (pool unoccupied)	0.5
Residential pool	0.5
Condominium	0.65
Therapy	0.65
Hotel	0.8
Public, schools	1.0
Whirlpools, spas	1.0
Wavepools, water slides	1.5 (minimum)

The effectiveness of controlling the natatorium environment depends on correct estimation of water evaporation rates. Applying the correct activity factors is extremely important in determining water evaporation rates. The difference in peak evaporation rates between private pools and active public pools of comparable size may be more than 100%.

Actual operating temperatures and relative humidity conditions should be established before design. How the area will be used usually dictates design (Table 1).

Air temperatures in public and institutional pools should be maintained 2 to 4°F above the water temperature (but not above the comfort threshold of 86°F) to reduce the evaporation rate and avoid chill effects on swimmers.

Ventilation Requirements

Air Quality. Outdoor air ventilation rates prescribed by ASHRAE *Standard* 62.1 are intended to provide acceptable air quality conditions for the average pool using chlorine for primary disinfection. The ventilation requirement may be excessive for private pools and installations with low use, and may also prove inadequate for high-occupancy public or waterpark-type installations.

Air quality problems in pools and spas are often caused by water quality problems, so simply increasing ventilation rates may prove both expensive and ineffective. Water quality conditions are a direct function of pool use and the type and effectiveness of water disinfection used.

Because indoor pools usually have high ceilings, temperature stratification can have a detrimental effect on indoor air quality. Careful duct layout must ensure that the space receives proper air changes and homogeneous air quality throughout. Some air movement at the deck and pool water level is essential to ensure acceptable air quality. Complaints from swimmers indicate that the greatest chloramine (see the section on Pool Water Chemistry) concentrations occur at the water surface. Children are especially vulnerable to the ill effects of chloramine inhalation.

Exhaust air from pools is rich in moisture and may contain high levels of corrosive chloramine compounds. Although most codes allow pool air to be used as makeup for showers, toilets, and locker rooms, these spaces should be provided with separate ventilation and maintained at a positive pressure with respect to the pool.

Pool and spa areas should be maintained at a negative pressure of 0.05 to 0.15 in. of water relative to adjacent areas of the building to prevent chloramine odor migration. Active methods of pressure control may prove more effective than static balancing and may be necessary where outdoor air is used as a part of an active humidity control strategy. Openings from the pool to other areas should be minimized and controlled. Passageways should be equipped with doors with automatic closers to inhibit migration of moisture and air.

Exhaust air intake grilles should be located as close as possible to the warmest body of water in the facility. Warmer waters and those with high agitation levels offgas chemicals at higher rates compared to traditional pools. This also allows body oils to become airborne. Ideally these pollutants should be removed from close to the source

before they have a chance to diffuse and negatively impact the air quality. Installations with intakes directly above whirlpools have resulted in the best air quality.

Air Delivery Rates. Most codes require a minimum of six air changes per hour, except where mechanical cooling is used. This rate may prove inadequate for some occupancy and use.

Where mechanical dehumidification is provided, air delivery rates should be established to maintain appropriate conditions of temperature and humidity. The following rates are typically desired:

Pools with no spectator areas	4 to 6 air changes per hour
Spectator areas	6 to 8 air changes per hour
Therapeutic pools	4 to 6 air changes per hour

Outdoor air delivery rates may be constant or variable, depending on design. Minimum rates, however, must provide adequate dilution of contaminants generated by pool water and must maintain acceptable ventilation for occupancy.

Where a minimum outdoor air ventilation rate is established to protect against condensation in a building's structural elements, the rates are typically used for 100% outdoor air systems. These rates usually result in excessive humidity levels under most operating conditions and are generally not adequate to produce acceptable indoor air quality, especially in public facilities subject to heavy use.

Duct Design

As with any installation, proper duct design and installation is necessary for proper equipment performance. Poorly installed return duct connections, for example, can significantly reduce the performance of a dehumidifier. The following duct construction practices apply to natatoriums:

- Fiberglass duct liner should not be used. Where condensation may occur, the insulation must be applied to the duct exterior.
- Duct materials and hardware must be resistant to chemical corrosion from the pool atmosphere. Stainless steels, even the 316 series, are not recommended because they are readily attacked by chlorides and are prone to pitting. Galvanized steel, fabric (with adjustable grilles sewn in), or aluminum sheet metal may be used for exposed duct systems. Buried ductwork should be constructed from nonmetallic fiberglass-reinforced or PVC materials because of the more demanding environment.
- Grilles, registers, and diffusers should be constructed from aluminum. They should be selected for low static pressure loss and for appropriate throws for proper air distribution.
- Supply air should be directed against interior envelope surfaces prone to condensation (glass and doors). Some supply air should be directed over the water surface to move contaminated air toward an exhaust point and control chloramines released at the water surface. However, air movement over the pool water surface must not exceed 30 fpm [as per the evaporation rate w_p in Equation (1)].
- Return air inlets should be located to recover warm, humid air and return it to the ventilation system for treatment, to prevent supply air from short-circuiting and to minimize recirculation of chloramines.
- Exhaust air inlets should be located to maximize capture effectiveness and minimize recirculation of chloramines. Exhausting from directly above whirlpools is also desirable. Exhaust air should be taken directly to the outside, through heat recovery devices where provided.
- Filtration should be selected to provide 45 to 65% efficiencies (as defined in ASHRAE *Standard* 52.1) and be installed in locations selected to prevent condensation in the filter bank. Filter media and support materials should be resistant to moisture degradation.
- Air systems may be designed for noise levels of NC 45 to 50; however, wall, floor, and ceiling surfaces should be evaluated for their attenuation effect.

Envelope Design

Glazing in exterior walls becomes susceptible to condensation when the outdoor temperature drops below the pool room dew point. The design goal is to maintain the surface temperature of the glass and the window frames a minimum of 5°F above the pool room dew point. Windows must allow unobstructed air movement on inside surfaces. Thermal break frames should be used. Avoid recessed windows and protruding window frames. Skylights are especially vulnerable, and require attention to control condensation. Wall and roof vapor retarder designs should be carefully reviewed, especially at wall-to-wall and wall-to-roof junctures and at window, door, and duct penetrations. The pool enclosure must be suitable for year-round operation at 50 to 60% relative humidity. A vapor barrier analysis (as in Figure 2 in Chapter 23 of the 2005 *ASHRAE Handbook—Fundamentals*) should be prepared. Failure to install an effective vapor retarder will result in condensation forming in the structure, and potentially serious damage.

Pool Water Chemistry

Failure to maintain proper chemistry in the pool water causes serious air quality problems and deterioration of mechanical systems and building components. Water treatment equipment and chemicals should be located in a separate, dedicated, well-ventilated space that is under negative pressure. Pool water treatment consists of primary disinfection, pH control, water filtration and purging, and water heating. For further information, refer to Kowalsky (1990).

Air quality problems are usually caused by the reaction of chlorine with biological wastes, and particularly with ammonia, which is a by-product of the breakdown of urine and perspiration. Chlorine reacts with these wastes, creating chloramines (monochloramine, dichloramine, and nitrogen trichloride) that are commonly measured as combined chlorine. Adding chemicals to pool water increases total contaminant levels. In high-occupancy pools, water contaminant levels can double in a single day of operation.

Chlorine's efficiency at reducing ammonia is affected by several factors, including water temperature, water pH, total chlorine concentration, and level of dissolved solids in the water. Because of their higher operating temperature and higher ratio of occupancy per unit water volume, spas produce greater quantities of air contaminants than pools.

The following measures have demonstrated a potential to reduce chloramine concentrations in the air and water:

- **Ozonation.** In low concentrations, ozone has substantially reduced the concentration of combined chlorine in the water. In high concentrations, ozone can replace chlorine as the primary disinfection process; however, ozone is unable to maintain sufficient residual levels in the water to maintain a latent biocidal effect. This necessitates maintenance of chlorine as a residual process at concentrations of 0.5 to 1.5 ppm.
- **Water Exchange Rates.** High concentrations of dissolved solids in water have been shown to directly contribute to high combined chlorine (chloramine) levels. Adequate water exchange rates are necessary to prevent the buildup of biological wastes and their oxidized components in pool and spa water. Conductivity measurement is an effective method to control the exchange rate of water in pools and spas to effectively maintain water quality and minimize water use. In high-occupancy pools, heat recovery may prove useful in reducing water heating energy requirements.

Energy Considerations

Natatoriums can be a major energy burden on facilities, so they represent a significant opportunity for energy conservation. Several design solutions are possible using both dehumidification and

ventilation strategies. When evaluating a system, energy consumed by all elements should be considered, including primary heating and cooling systems, fan motors, water heaters, and pumps.

Natatoriums with fixed outdoor air ventilation rates without dehumidification generally have seasonally fluctuating space temperature and humidity levels. Systems designed to provide minimum ventilation rates without dehumidification are unable to maintain relative humidity conditions within prescribed limits. These systems may facilitate mold and mildew growth and may be unable to provide acceptable indoor air quality. Peak dehumidification loads vary with activity levels and during the cooling season when ventilation air becomes an additional dehumidification load to the space.

FAIRS AND OTHER TEMPORARY EXHIBITS

Occasionally, large-scale exhibits are constructed to stimulate business, present new ideas, and provide cultural exchanges. Fairs of this type take years to construct, are open from several months to several years, and are sometimes designed considering future use of some buildings. Fairs, carnivals, or exhibits, which may consist of prefabricated shelters and tents that are moved from place to place and remain in a given location for only a few days or weeks, are not covered here because they seldom require the involvement of architects and engineers.

Design Concepts

One consultant or agency should be responsible for setting uniform utility service regulations and practices to ensure proper organization and operation of all exhibits. Exhibits that are open only during spring or fall months require a much smaller heating or cooling plant than those open during peak summer or winter months. This information is required in the earliest planning stages so that system and space requirements can be properly analyzed.

Occupancy

Fair buildings have heavy occupancy during visiting hours, but patrons seldom stay in any one building for a long period. The length of time that patrons stay in a building determines the air-conditioning design. The shorter the anticipated stay, the greater the leeway in designing for less-than-optimum comfort, equipment, and duct layout. Also, whether patrons wear coats and jackets while in the building influences operating design conditions.

Equipment and Maintenance

Heating and cooling equipment used solely for maintaining comfort and not for exhibit purposes may be secondhand or leased, if available and of the proper capacity. Another possibility is to rent the air-conditioning equipment to reduce the capital investment and eliminate disposal problems when the fair is over.

Depending on the size of the fair, length of operation time, types of exhibitors, and fair sponsors' policies, it may be desirable to analyze the potential for a centralized heating and cooling plant versus individual plants for each exhibit. The proportionate cost of a central plant to each exhibitor, including utility and maintenance costs, may be considerably less than having to furnish space and plant utility and maintenance costs. The larger the fair, the more savings may result. It may be practical to make the plant a showcase, suitable for exhibit and possibly added revenue. A central plant may also form the nucleus for commercial or industrial development of the area after the fair is over.

If exhibitors furnish their own air-conditioning plants, it is advisable to analyze shortcuts that may be taken to reduce equipment space and maintenance aids. For a 6-month to 2-year maximum operating period, for example, tube pull or equipment removal space is not needed or may be drastically reduced. Higher fan and pump motor power and smaller equipment are permissible

to save on initial costs. Ductwork and piping costs should be kept as low as possible because these are usually the most difficult items to salvage; cheaper materials may be substituted wherever possible. The job must be thoroughly analyzed to eliminate all unnecessary items and reduce all others to bare essentials.

The central plant may be designed for short-term use as well. However, if it is to be used after the fair closes, the central plant should be designed in accordance with the best practice for long-life plants. It is difficult to determine how much of the piping distribution system can be used effectively for permanent installations. For that reason, piping should be simply designed initially, preferably in a grid, loop, or modular layout, so that future additions can be made easily and economically.

Air Cleanliness

The efficiency of filters needed for each exhibit is determined by the nature of the area served. Because the life of an exhibit is very short, it is desirable to furnish the least expensive filtering system. If possible, one set of filters should be selected to last for the life of the exhibit. In general, filtering efficiencies do not have to exceed 30% (see ASHRAE *Standard* 52.1).

System Applicability

If a central air-conditioning plant is not built, equipment installed in each building should be the least costly to install and operate for the life of the exhibit. These units and systems should be designed and installed to occupy the minimum usable space.

Whenever feasible, heating and cooling should be performed by one medium, preferably air, to avoid running a separate piping and radiation system for heating and a duct system for cooling. Air curtains used on an extensive scale may, on analysis, simplify building structure and lower total costs.

Another possibility when both heating and cooling are required is a heat pump system, which may be less costly than separate heating and cooling plants. Economical operation may be possible, depending on the building characteristics, lighting load, and occupant load. If well or other water is available, it may produce a more economical installation than an air-source heat pump.

ATRIUMS

Atriums have diverse functions and occupancies. An atrium may (1) connect buildings; (2) serve as an architectural feature, leisure space, greenhouse, and/or smoke reservoir; and (3) afford energy and lighting conservation. The temperature, humidity, and hours of usage of an atrium are directly related to those of the adjacent buildings. Glass window walls and skylights are common. Atriums are generally large in volume with relatively small floor areas. The temperature and humidity conditions, air distribution, impact from adjacent buildings, and fenestration loads to the space must be considered in the design of an atrium.

Perimeter radiant heating (e.g., overhead, wall finned-tube, floor, or combinations thereof) is commonly used for expansive glass windows and skylights. Air-conditioning systems can heat, cool, and control smoke. Distribution of air across windows and skylights can also control heat transfer and condensation. Low supply and high return air distribution can control heat stratification, as well as wind and stack effects. Some atrium designs include a combination of high/low supply and high/low return air distribution to control heat transfer, condensation, stratification, and wind/stack effects.

The energy use of an atrium can be reduced by installing double- and triple-panel glass and mullions with thermal breaks, as well as shading devices such as external, internal, and interior screens, shades, and louvers.

Extensive landscaping is common in atriums. Humidity levels are generally maintained between 10 and 35%. Hot and cold air should not be distributed directly onto plants and trees.

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CHAPTER 5

HOTELS, MOTELS, AND DORMITORIES

HOTELS, motels, and dormitories may be single-room or multiroom, long- or short-term dwelling (or residence) units; they may be stacked sideways and/or vertically. Information in the first three sections of the chapter applies generally; the last three sections are devoted to the individual types of facilities.

LOAD CHARACTERISTICS

- Ideally, each room served by an HVAC unit should be able to be ventilated, cooled, heated, or dehumidified independently of any other room. If not, air conditioning for each room will be compromised.
- Typically, the space is not occupied at all times. For adequate flexibility, each unit's ventilation and cooling should be able to be shut off (except when humidity control is required), and its heating to be shut off or turned down.
- Concentrations of lighting and occupancy are typically low; activity is generally sedentary or light. Occupancy is transient in nature, with greater use of bedrooms at night.
- Kitchens, whether integrated with or separate from residential quarters, have the potential for high appliance loads, odor generation, and large exhaust requirements.
- Rooms generally have an exterior exposure; kitchens, toilets, and dressing rooms may not. The building as a whole usually has multiple exposures, as may many individual dwelling units.
- Toilet, washing, and bathing facilities are almost always incorporated in the dwelling units. Exhaust air is usually incorporated in each toilet area.
- The building has a relatively high hot-water demand, generally for periods of an hour or two, several times a day. This demand can vary from a fairly moderate and consistent daily load profile in a senior citizens building to sharp, unusually high peaks at about 6:00 PM in dormitories. Chapter 49 includes details on service water heating.
- Load characteristics of rooms, dwelling units, and buildings can be well defined with little need to anticipate future changes to design loads, other than adding a service such as cooling that may not have been incorporated originally.
- The prevalence of shifting, transient interior loads and exterior exposures with glass results in high diversity factors; the long-hour usage results in fairly high load factors.

DESIGN CONCEPTS AND CRITERIA

Wide load swings and diversity within and between rooms require a flexible system design for 24-hour comfort. Besides opening windows, the only way to provide flexible temperature control is having individual room components under individual room control that can cool, heat, and ventilate independently of equipment in other rooms.

The preparation of this chapter is assigned to TC 9.8, Large Building Air-Conditioning Applications.

In some climates, summer humidity becomes objectionable because of the low internal sensible loads that result when cooling is on/off controlled. Modulated cooling and/or reheat may be required to achieve comfort. Reheat should be avoided unless some sort of heat recovery is involved.

Dehumidification can be achieved by lowering cooling coil temperatures and reducing airflow. Another means of dehumidification is desiccant dehumidifiers.

Some people have a noise threshold low enough that certain types of equipment disturb their sleep. Higher noise levels may be acceptable in areas where there is little need for air conditioning. Medium- and better-quality equipment is available with noise criteria (NC) 35 levels at 10 to 14 ft in medium to soft rooms and little sound change when the compressor cycles.

Perimeter fan coils are usually quieter than unitary systems, but unitary systems provide more redundancy in case of failure.

SYSTEMS

Energy-Efficient Systems

The most efficient systems generally include water-source and air-source heat pumps. In areas with ample solar radiation, water-source heat pumps may be solar assisted. Energy-efficient equipment generally has the lowest operating cost and is relatively simple, an important factor where skilled operating personnel are unlikely to be available. Most systems allow individual operation and thermostatic control. The typical system allows individual metering so that most, if not all, of the cooling and heating costs can be metered directly to the occupant (McClelland 1983). Existing buildings can be retrofitted with heat flow meters and timers on fan motors for individual metering.

The water-loop heat pump has a lower operating cost than air-cooled unitary equipment, especially where electric heat is used. The lower installed cost encourages its use in mid- and high-rise buildings where individual dwelling units have floor areas of 800 ft^2 or larger. Some systems incorporate sprinkler piping as the water loop.

Except for the central circulating pump, heat rejector fans, and supplementary heater, the water-loop heat pump is predominantly decentralized; individual metering allows most of the operating cost to be paid by the occupant. Its life should be longer than for other unitary systems because most of the mechanical equipment is in the building and not exposed to outdoor conditions. Also, load on the refrigeration circuit is not as severe because water temperature is controlled for optimum operation. Operating costs are low because of the system's inherent energy conservation. Excess heat may be stored during the day for the following night, and heat may be transferred from one part of the building to another.

Although heating is required in many areas during cool weather, cooling may be needed in rooms having high solar or internal loads. On a mild day, surplus heat throughout the building is frequently transferred into the hot-water loop by water-cooled condensers on cooling cycle, so that water temperature rises. The heat remains

stored in the water and can be extracted at night; a water heater is not needed. This heat storage is improved by the presence of a greater mass of water in the pipe loop; some systems include a storage tank for this reason. Because the system is designed to operate during the heating season with water supplied at a temperature as low as 60°F, the water-loop heat pump lends itself to solar assist; relatively high solar collector efficiencies result from the low water temperature.

The installed cost of the water-loop heat pump is higher in very small buildings. In severe cold climates with prolonged heating seasons, even where natural gas or fossil fuels are available at reasonable cost, the operating cost advantages of this system may diminish unless heat can be recovered from some another source, such as solar collectors, geothermal, or internal heat from a commercial area served by the same system.

Energy-Neutral Systems

To qualify as energy-neutral, a system must have controls that prevent simultaneous operation of the cooling and heating cycles. Some examples are (1) packaged terminal air conditioners (PTACs) (through-the-wall units), (2) window units or radiant ceiling panels for cooling combined with finned or baseboard radiation for heating, (3) unitary air conditioners with an integrated heating system, (4) fan coils with remote condensing units, and (5) variable-air-volume (VAV) systems with either perimeter radiant panel heating or baseboard heating. For unitary equipment, control may be as simple as a heat/cool switch. For other types, dead-band thermostatic control may be required.

PTACs are frequently installed to serve one or two rooms in buildings with mostly small, individual units. In a common two-room arrangement, a supply plenum diverts some of the conditioned air serving one room into the second, usually smaller, room. Multiple PTAC units allow additional zoning in dwellings with more rooms. Additional radiation heat is sometimes needed around the perimeter in cold climates.

Heat for a PTAC may be supplied either by electric resistance heaters or by hot-water or steam heating coils. Initial costs are lower for a decentralized system using electric resistance heat. Operating costs are lower for coils heated by combustion fuels. Despite its relatively inefficient refrigeration circuits, a PTAC's operating cost is quite reasonable, mostly because of individual thermostatic control over each machine, which eliminates the use of reheat while preventing the space from being overheated or overcooled. Also, because equipment is located in the space being served, little power is devoted to circulating the room air. Servicing is simple: a defective machine is replaced by a spare chassis and forwarded to a service organization for repair. Thus, building maintenance can be done by relatively unskilled personnel.

Noise levels are generally no higher than NC 40, but some units are noisier than others. Installations near a seacoast should be specially constructed (usually with stainless steel or special coatings) to avoid accelerated corrosion of aluminum and steel components caused by salt. In high-rise buildings of more than 12 stories, special care is required, both in design and construction of outside partitions and in installation of air conditioners, to avoid operating problems associated with leakage (caused by stack effect) around and through the machines.

Frequently, the least expensive installation is finned or baseboard radiation for heating and window-type room air conditioners for cooling. The window units are often purchased individually by the building occupants. This choice offers a reasonable operating cost and is relatively simple to maintain. However, window units have the shortest equipment life, highest operating noise level, and poorest distribution of conditioned air of any systems discussed in this section.

Fan-coils with remote condensing units are used in smaller buildings. Fan-coil units are located in closets, and the ductwork distributes air to the rooms in the dwelling. Condensing units may be located on roofs, at ground level, or on balconies.

Low-capacity residential warm-air furnaces may be used for heating, but with gas- or oil-fired units, combustion products must be vented. In a one- or two-story structure, it is possible to use individual chimneys or flue pipes, but in a high-rise structure requires a multiple-vent chimney or a manifold vent. Local codes should be consulted.

Sealed combustion furnaces draw all combustion air from outside and discharge flue products through a windproof vent to the outdoors. The unit must be located near an outside wall, and exhaust gases must be directed away from windows and intakes. In one- or two-story structures, outdoor units mounted on the roof or on a pad at ground level may also be used. All of these heating units can be obtained with cooling coils, either built-in or add-on. Evaporative-type cooling units are popular in motels, low-rise apartments, and residences in mild climates.

Desiccant dehumidification should be considered when independent control of temperature and humidity is required to avoid reheat.

Energy-Inefficient Systems

Energy-inefficient systems allow simultaneous cooling and heating. Examples include two-, three-, and four-pipe fan coil units, terminal reheat systems, and induction systems. Some units, such as the four-pipe fan coil, can be controlled so that they are energy-neutral. They are primarily used for humidity control.

Four-pipe systems and two-pipe systems with electric heaters can be designed for complete temperature and humidity flexibility during summer and intermediate season weather, although none provides winter humidity control. Both systems provide full dehumidification and cooling with chilled water, reserving the other two pipes or an electric coil for space heating or reheat. The equipment and necessary controls are expensive, and only the four-pipe system, if equipped with an internal-source heat-recovery design for the warm coil energy, can operate at low cost. When year-round comfort is essential, four-pipe systems or two-pipe systems with electric heat should be considered.

Total Energy Systems

A total energy system is an option for any multiple or large housing facility with large year-round service water heating requirements. Total energy systems are a form of cogeneration in which all or most electrical and thermal energy needs are met by on-site systems as described in Chapter 7 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*. A detailed load profile must be analyzed to determine the merits of using a total energy system. The reliability and safety of the heat-recovery system must also be considered.

Any of the previously described systems can perform the HVAC function of a total energy system. The major considerations as they apply to total energy in choosing a HVAC system are as follows:

- Optimum use must be made of thermal energy recoverable from the prime mover during all or most operating modes, not just during conditions of peak HVAC demand.
- Heat recoverable through the heat pump may become less useful because the heat required during many of its potential operating hours will be recovered from the prime mover. The additional investment for heat pump or heat recovery cycles may be more difficult to justify because operating savings are lower.
- The best application for recovered waste heat is for those services that use only heat (i.e., service hot water, laundry facilities, and space heating).

Special Considerations

Local building codes govern ventilation air quantities for most buildings. Where they do not, ASHRAE *Standard* 62.1 should be

followed. The quantity of outdoor air introduced into rooms or corridors is usually slightly in excess of the exhaust quantities to pressurize the building. To avoid adding load to individual systems, outdoor air should be treated to conform to indoor air temperature and humidity conditions. In humid climates, special attention must be given to controlling humidity from outdoor air. Otherwise, the outdoor air may reach corridor temperature while still retaining a significant amount of moisture.

In buildings having a centrally controlled exhaust and supply, the system is regulated by a time clock or a central management system for certain periods of the day. In other cases, the outside air may be reduced or shut off during extremely cold periods, although this practice is not recommended and may be prohibited by local codes. These factors should be considered when estimating heating load.

For buildings using exhaust and supply air on a 24-hour basis, air-to-air heat recovery devices may be merited (see Chapter 44 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment)*. These devices can reduce energy consumption by capturing 60 to 80% of the sensible and latent heat extracted from the air source.

Infiltration loads in high-rise buildings without ventilation openings for perimeter units are not controllable year-round by general building pressurization. When outer walls are pierced to supply outdoor air to unitary or fan-coil equipment, combined wind and thermal stack-effect forces create equipment operating problems. These factors must be considered for high-rise buildings (see Chapter 27 of the 2005 *ASHRAE Handbook—Fundamentals*).

Interior public corridors should have tempered supply air with transfer into individual area units, if necessary, to provide kitchen and toilet makeup air requirements. Transfer louvers need to be acoustically lined. Corridors, stairwells, and elevators should be pressurized for fire and smoke control (see Chapter 52).

Kitchen air can be recirculated through hoods with activated charcoal filters rather than exhausted. Toilet exhaust can be VAV with a damper operated by the light switch. A controlled source of supplementary heat in each bathroom is recommended to ensure comfort while bathing.

Air-conditioning equipment must be isolated to reduce noise generation or transmission. The cooling tower or condensing unit must be designed and located to avoid disturbing occupants of the building or of adjacent buildings.

An important but frequently overlooked load is the heat gain from piping for hot-water services. Insulation thickness should conform to the latest local energy codes and standards at a minimum. In large, luxury-type buildings, a central energy or building management system allows supervision of individual air-conditioning units for operation and maintenance.

Some facilities conserve energy by reducing indoor temperature during the heating season. Such a strategy should be pursued with caution because it could affect occupant comfort, and, for example, the competitiveness of a hotel/motel.

HOTELS AND MOTELS

Hotel and motel accommodations are usually single guest rooms with a toilet and bath adjacent to a corridor, and flanked on both sides by other guest rooms. The building may be single-story, low-rise, or high-rise. Multipurpose subsidiary facilities range from stores and offices to ballrooms, dining rooms, kitchens, lounges, auditoriums, and meeting halls. Luxury motels may be built with similar facilities. Occasional variations are seen, such as kitchenettes, multiroom suites, and outside doors to patios and balconies. Hotel classes range from the deluxe hotel to the economy hotel/motel as outlined in Table 1.

A hotel can be divided into three main areas:

1. Guest rooms
2. Public areas
   - Lobby, atrium, and lounges
   - Ballrooms
   - Meeting rooms
   - Restaurants and dining rooms
   - Stores
   - Swimming pools
   - Health clubs
3. Back-of-the-house (BOTH) areas
   - Kitchens
   - Storage areas
   - Laundry
   - Offices
   - Service areas and equipment rooms

The two main areas of use are the guest rooms and the public areas. Maximum comfort in these areas is critical to success of any hotel. Normally the BOTH spaces are less critical than the remainder of the hotel with the exception of a few spaces where a controlled environment is required or recommended.

Guest Rooms

Air conditioning in hotel rooms should be quiet, easily adjustable, and draft free. It must also provide ample outside air. Because the hotel business is so competitive and space is at a premium, systems that require little space and have low total owning and operating costs should be selected.

Design Concepts and Criteria. Table 2 lists design criteria for hotel guest rooms. In addition, the design criteria for hotel room HVAC services must consider the following factors:

- Individual and quickly responding temperature control
- Draft-free air distribution
- Toilet room exhaust
- Ventilation (makeup) air supply

Table 1   Hotel Classes

Type of Facility	Typical Occupancy, Persons per Room	Characteristics
Deluxe hotel	1.2	Large rooms, suites, specialty restaurants
Luxury/first class, full-service hotel	1.2 to1.3	Large rooms, large public areas, business center, pool and health club, several restaurants
Mid-scale, full-service hotel	1.2 to 1.3	Large public areas, business center, several restaurants
Convention hotel	1.4 to 1.6	Large number of rooms, very large public areas, extensive special areas, rapid shifting of peak loads
Limited-service hotel	1.1	Limited public areas, few restaurants, may have no laundry
Upscale, all-suites hotel	2.0	Rooms are two construction bays, in-room pantries, limited public areas, few restaurants
Economy, all-suites hotel	2.0 to 2.2	Smaller suites, limited public areas and restaurants
Resort hotel	1.9 to 2.4	Extensive public areas, numerous special and sport areas, several restaurants
Conference center	1.3 to 1.4	Numerous special meeting spaces, limited dining options
Casino hotel	1.5 to 1.6	Larger rooms, large gaming spaces, extensive entertainment facilities, numerous restaurants
Economy hotel/motel	1.6 to 1.8	No public areas, little or no dining, usually no laundry

Table 2 Hotel Design Criteria[a,b]

Category	Inside Design Conditions				Ventilation[d]	Exhaust[e]	Filter Efficiency[f]	Noise, RC Level
	Winter		Summer					
	Temperature	Relative Humidity[c]	Temperature	Relative Humidity				
Guest rooms	74 to 76°F	30 to 35%	74 to 78°F	50 to 60%	30 to 60 cfm per room	20 to 50 cfm per room	6 to 8 MERV	25 to 35
Lobbies	68 to 74°F	30 to 35%	74 to 78°F	40 to 60%	15 cfm per person	—	8 MERV or better	35 to 45
Conference/ Meeting rooms	68 to 74°F	30 to 35%	74 to 78°F	40 to 60%	20 cfm per person	—	8 MERV or better	25 to 35
Assembly rooms	68 to 74°F	30 to 35%	74 to 78°F	40 to 60%	15 cfm per person	—	8 MERV or better	25 to 35

[a] This table should not be the only source for design criteria. Data contained here can be determined from volumes of the *ASHRAE Handbook*, standards, and governing local codes.
[b] Design criteria for stores, restaurants, and swimming pools are in Chapters 2, 3, and 4, respectively.
[c] Minimum recommended humidity.
[d] Per ASHRAE *Standard* 62.1.
[e] Air exhaust from bath and toilet area.
[f] Per ASHRAE *Standard* 52.2 (MERV = minimum efficiency reporting values).

- Humidity control
- Acceptable noise level
- Simple controls
- Reliability
- Ease of maintenance
- Operating efficiency
- Use of space

Load Characteristics. The great diversity in the design, purpose, and use of hotels and motels makes analysis and load studies very important. Load diversification is possible because of guest rooms' transient occupancy and the diversity associated with support facility operation.

The envelope cooling and heating load is dominant because the guest rooms normally have exterior exposures. Other load sources such as people, lights, appliances, etc. are a relatively small part of the space sensible and latent loads. The ventilation load can represent up to 15% of the total cooling load.

Because of the nature of the changing envelope sensible load and the transient occupancy of the guest room, large fluctuations in the space sensible load in a one-day cycle are common. The ventilation sensible cooling load can vary from 0 to 100% in a single day, whereas the ventilation latent load can remain almost constant for the entire day. A low sensible heat ratio is common in moderate to very humid climates. Usually, the HVAC equipment must only handle part or low loads and peak loads rarely occur. For example, in humid climates, introducing untreated outside air directly into the guest room or into the return air plenum of the HVAC unit operating at part or low load creates a severe high-humidity problem, which is one of the causes of mold and mildew. The situation is further aggravated when the HVAC unit operates in on/off cycle during part- or low-load conditions.

Applicable Systems. Most hotels use all-water or unitary refrigerant-based equipment for guest rooms. All-water systems include

- Two-pipe fan-coils
- Two-pipe fan-coil with electric heat
- Four-pipe fan-coils

Unitary refrigerant-based systems include

- Packaged terminal air conditioner or packaged terminal heat pump (with electric heat)
- Air-to-air heat pump (ductless, split)
- Water-source heat pump

Except for the two-pipe fan-coil, all these systems cool, heat, or dehumidify independently of any other room and regardless of the season. A two-pipe fan-coil system should be selected only when economics and design objectives dictate a compromise to performance. Selection of a particular system should be based on

- First cost
- Economical operation, especially at part load
- Maintainability

Compared to unitary refrigerant-based units, all-water systems offer the following advantages:

- Reduced total installed cooling capacity due to load diversity
- Lower operating cost due to a more efficient central cooling plant
- Lower noise level (compared to PTAC and water-source heat pump)
- Longer service life
- Less equipment to be maintained in the occupied space
- Less water in circulation (compared to water-source heat pump)
- Smaller pipes and pumps (compared to water-source heat pump)

Unitary refrigerant-based systems offer the following advantages:

- Lower first cost
- Immediate all year availability of heating and cooling
- No seasonal changeover required
- Cooling available without operating a central refrigeration plant
- Can transfer energy from spaces being cooled to spaces being heated (with water-source heat pump)
- Range of circulated water temperature requires no pipe insulation (for water-source heat pump)
- Less dependence on a central plant for heating and cooling
- Simplicity, which results in lower operating and maintenance staff costs

The type of facility, sophistication, and quality desired by the owner/operator, as well as possible code requirements typically influence the selection. An economic analysis (life-cycle cost) is particularly important when selecting the most cost-effective system. Chapter 36 has further information on economic analysis techniques. Computer software like the NIST Building Life-Cycle Cost Program (BLCC) performs life-cycle cost analyses quickly and accurately (NIST 2006).

Chapters 3 and 5 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment* provide additional information about all-water systems and unitary refrigerant-based systems.

Room fan-coils and room unitary refrigerant-based units are available in many configurations, including horizontal, vertical, exposed, and concealed. The unit should be located in the guest room so that it provides excellent air diffusion without creating unpleasant drafts. Air should not discharge directly over the head of the bed, to keep cold air away from a sleeping guest. The fan-coil/heat pump unit is most commonly located

- Above the ceiling in the guest room entry corridor or above the bathroom ceiling (horizontal air discharge),
- On the room's perimeter wall (vertical air discharge), or
- In a floor-to-ceiling enclosed chase (horizontal air discharge).

Locating the unit above the entry corridor is preferred because air can flow directly along the ceiling and the unit is relatively accessible for maintenance (see Figures 1 and 2).
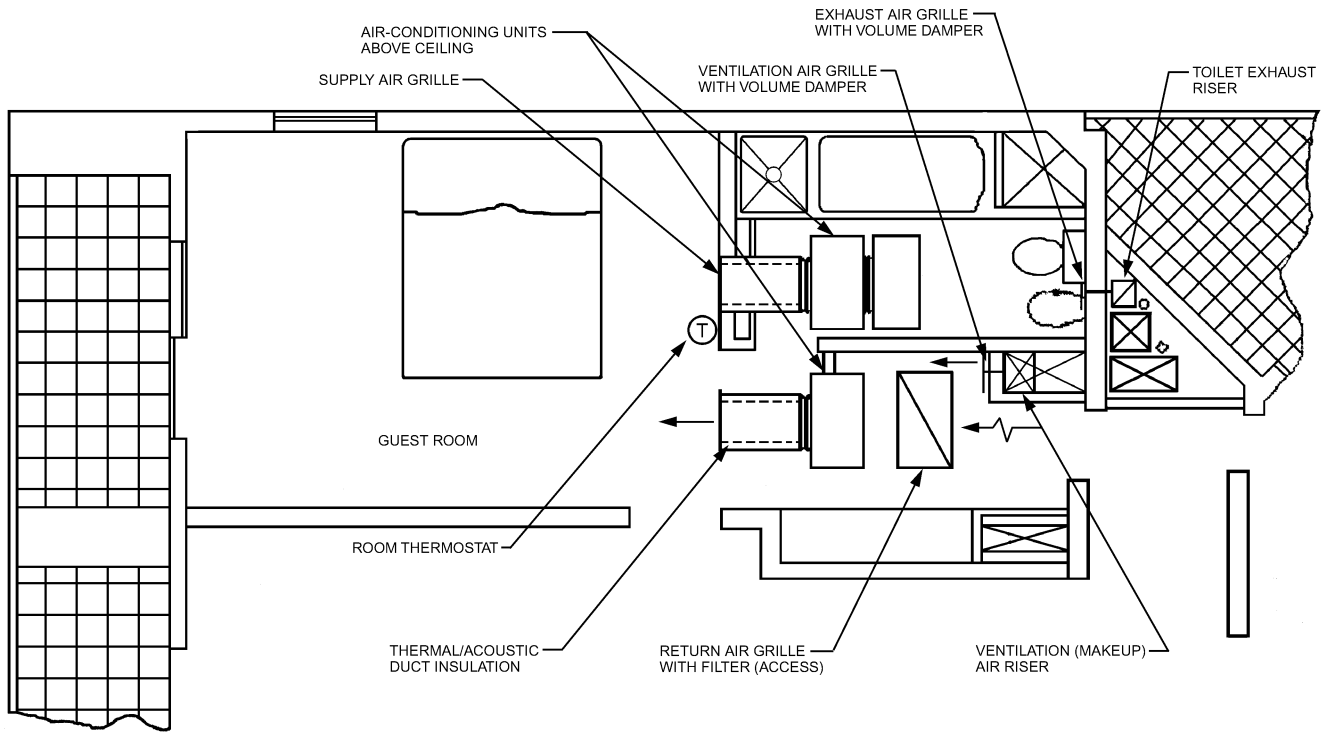
**Fig. 1 Alternative Location for Hotel Guest Room Air-Conditioning Unit
above Hung Ceiling**
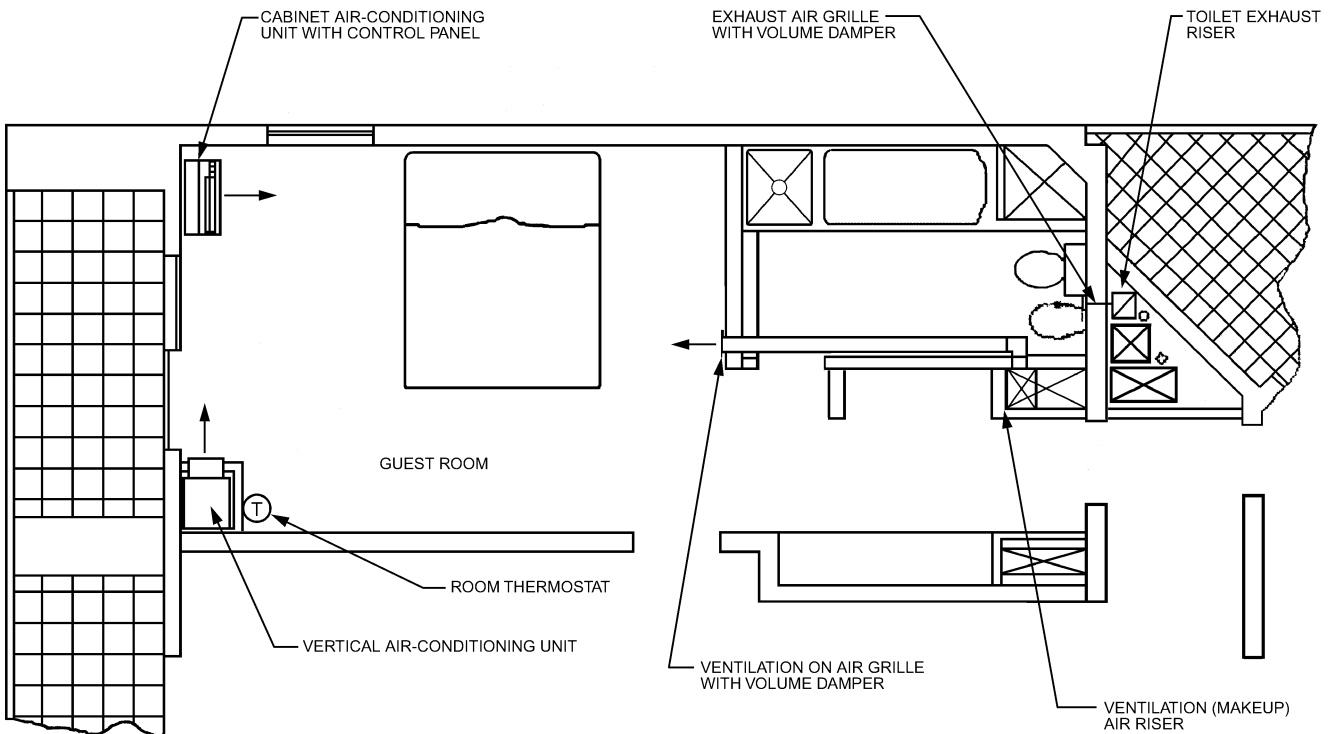
**Fig. 2 Alternative Location for Hotel Guest Room Air-Conditioning Unit on Room Perimeter
and Chase-Enclosed**

Most units are designed for free-air discharge. The supply air grille should be selected according to the manufacturer's recommendations for noise and air diffusion. Also, airflow should not interfere with the room drapes or other wall treatment.

Other factors that should be considered include

- Sound levels at all operating modes, particularly with units that cycle on and off
- Adequately sized return air grille
- Access for maintenance, repair, and filter replacement

Ventilation (makeup) supply and exhaust rates must meet local code requirements. Ventilation rates vary and the load imposed by ventilation must be considered.

Providing conditioned ventilation air directly to the guest room is the preferred approach. Normally, outside air is conditioned in a primary makeup air unit and distributed by a primary air duct to every guest room. This approach controls the supply air conditions, ensures satisfactory room conditions and room air balance (room pressurization) even during part- or no-load conditions, and controls mold and mildew.

Other ventilation techniques are to

- Transfer conditioned ventilation air from the corridor to each guest room. This approach controls ventilation air conditions better; however, the air balance (makeup versus exhaust) in the guest room may be compromised. This approach is prohibited under many code jurisdictions.
- Introduce unconditioned outside air directly to the air-conditioning unit's return air plenum (perimeter wall installations). This approach can cause mold and mildew and should be avoided. During periods of part or low load, which occur during most of the cooling season, the thermostatically controlled air conditioner does not adequately condition the constant flow of outside air because the cooling coil valve closes and/or the compressor cycles off. As a result, humidity in the room increases. Also, when the air conditioner's fan is off, outside air infiltrates through the ventilation opening and again elevates the room's humidity level.

Guest-room HVAC units are normally controlled by a room thermostat. Thermostats for fan-coils normally control valves in two-pipe, four-pipe, and two-pipe chilled-water/electric heat systems. Control should include dead-band operation to separate the heating and cooling set points. Two-pipe system control valves are normally equipped with automatic changeover, which senses the water temperature and changes operation from heating to cooling. The thermostat may provide modulation or two-position control of the water control valve. The fan can be adjusted to high, medium, or low speed on most units.

Typical unitary refrigerant-based units have a push button off/fan/heat/cool selector switch, adjustable thermostat, and fan cycle switch. Heat pumps include a defrost cycle to remove ice from the outdoor coil. Chapter 46 has more information on control for fan coils.

Public Areas

Public areas are generally the showcase of a hotel. Special attention must be paid to incorporating a satisfactory system into the interior design. Locations of supply diffusers, grilles. air outlets. etc. must be coordinated to satisfy the architect. The HVAC designer must pay attention to access doors for servicing fire dampers, volume dampers, valves, and variable-air-volume (VAV) terminals.

Design Concepts and Criteria. Design criteria for public areas are given in Table 2. In addition, the following design criteria must be considered:

- Year-round availability of heating and cooling
- Independent unit for each main public area

- Economical and satisfactory operation at part- and low-load conditions
- Coordination with adjacent back-of-the-house (BOTH) areas to ensure proper air pressurization (e.g., restaurants, kitchens)

Load Characteristics. The hours each public area is used vary widely. In many cases, the load is from internal sources from people, lights, and equipment. The main lobby normally is operational 24 hours per day. Areas like restaurants, meeting rooms, and retail areas have intermittent use, so the load changes frequently. HVAC systems that respond effectively and economically must be selected for these areas.

Applicable Systems. All-air systems, single-duct constant-volume, and VAV are most frequently used for public areas. Chapter 2 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment* has more information on these systems, and Chapter 46 in this volume covers control for all-air VAV systems.

Back-of-the-House (BOTH) Areas

The BOTH area is normally considered a service or support area. Climatic conditions in these areas are typically less critical than in the remainder of the hotel. However, a few spaces require special attention.

Design Concepts and Criteria. Recommended design criteria for several areas in the BOTH are shown in Table 3.

Special Concerns

Humidity, Mildew, Moisture Control, and IAQ. Humidity control is critical to ensure satisfactory air quality and to minimize costly mold and mildew problem in hotels. Moisture can be introduced and infiltrate into the guest rooms in the following ways:

- Unconditioned ventilation air is delivered directly into the guest room through the HVAC unit. At part or low sensible loads or in situations where the unit cycles on and off, the air-conditioning unit will not dehumidify the air adequately to remove the excess moisture.
- Outdoor humid air infiltrates through openings, cracks, gaps. shafts, etc. because of insufficient space pressurization.
- Moisture migrates through external walls and building elements because of a vapor pressure differential.
- An internal latent load or moisture is generated.

Removing water vapor from the air is the most feasible way to control mold and mildew, particularly when the problem spreads to walls and carpeting. Good moisture control can be achieved by applying the following techniques:

Table 3   Design Criteria for Hotel Back-of-the-House Areas[a]

Category	Inside Design Conditions	Comments
Kitchen, general[b]	82°F	Provide spot cooling
pastry[b]	76°F	
chef's office[b]	74 to 78°F 50 to 60% rh (summer) 30 to 35% rh (winter)	Fully air conditioned
Housekeeper's office	74 to 78°F 50 to 60% rh (summer) 30 to 35% rh (winter)	Fully air conditioned
Telephone equipment room	Per equipment criteria	Stand-alone air conditioner; air conditioned all year
Wine storage	Per food and beverage manager criteria	Air conditioned all year
Laundry		Spot cooling as required at workstations

[a] Governing local codes must be followed for design of the HVAC.
[b] Consult Chapter 31 for details on kitchen ventilation.

- Introduce adequately dried ventilation (makeup) air [i.e., with a dew point of 53°F (60 grains/lb of dry air) or less] directly to the guest room.
- Maintain slightly positive pressure in the guest room to minimize infiltration of hot and humid air into the room. Before a new HVAC system is accepted by the owner, a certified air balance contractor should be engaged to demonstrate that the volume of dry makeup air exceeds the volume of exhaust air. As the building ages, it is important to maintain this slight positive pressure; otherwise, humid air that infiltrates into the building cavities will be absorbed regardless of how dry the room is maintained (Banks 1992).
- Provide additional dehumidification capability to the ventilation (makeup air) by dehumidifying the air to a lower level than the desired space humidity ratio. For example, introducing 60 cfm of makeup air at 55 gr/lb can provide approximately 400 Btu/h of internal latent cooling (assuming 65 gr/lb is a desirable space humidity ratio).
- Allow air conditioning to operate in unoccupied rooms instead of turning the units off, especially in humid areas.
- Improve the room envelope by increasing its vapor and infiltration resistance.

The third method allows ventilation air to handle part of the internal latent load (people, internal moisture generation, and moisture migration from external walls and building elements). In addition, this method can separate the internal sensible cooling, internal latent cooling, and ventilation loads. Independent ventilation/dehumidification allows room pressurization and space humidity control regardless of the mode of operation or magnitude of the air-conditioning load. Desiccant dehumidifiers can be retrofitted to solve existing moisture problems.

Dedicated Outdoor Air Systems (DOAS). DOAS air units are designed to condition ventilation air introduced into a space and to replace air exhausted from the building. The geographic location and class of the hotel dictate the functions of the makeup air units, which may filter, heat, cool, humidify, and/or dehumidify the ventilation air. Makeup air may be treated directly or by air-to-air heat recovery (sensible or combined sensible and latent) and other heat recovery techniques. Equipment to condition the air by air-to-air heat recovery and final heating, cooling, humidification, and/or dehumidification is also available.

Chapter 28 of the 2005 *ASHRAE Handbook—Fundamentals* provides design weather data for ventilation. Analyzing and selecting the proper makeup unit for the full range of entering conditions are critical for efficient and sufficient all-year operation. Air-to-air heat recovery helps stabilize entering conditions, which helps provide efficient and stable operation. However, heat recovery may not always be feasible. Often, exhaust air comes from many individual stacks. In this case, the cost of combining many exhausts for heat recovery may not be warranted.

Typical design criteria for ventilation (makeup) air units are listed in Table 4.

Table 4 Design Criteria for Hotel Guest Room DOAS

Supply Air Conditions				Filter Efficiency (ASHRAE *Standard 52.2)*
Winter		Summer		
Temperature	Relative Humidity	Temperature	Relative Humidity	
68 to 76°F	30 to 45%	74 to 78°F	40 to 50%	6 to 8 MERV

Notes:
1. Follow local codes when applicable.
2. Building location may dictate optimum supply condition in recommended range.
3. MERV = minimum efficiency rating values.

Makeup air units can be stand alone packaged (unitary) or integrated in an air handler. A typical makeup air unit usually has the following features:

- Heating, cooling, and dehumidification
  - Chilled/hot water or steam coils in the air handling unit
  - Unitary refrigerant-based unit (direct-expansion cooling and gas furnace or electric heat)
  - Air-to-air energy recovery combined with mechanical cooling (DX or chilled water) and heating
  - Desiccant-based dehumidifier combined with air-to-air energy recovery, indirect/direct evaporative cooling and supplementary mechanical cooling and heating
- Heating only
  - Hot water or steam coils in the air handling unit
  - Stand alone gas-fired or electric makeup units
  - Air-to-air energy recovery with supplement heat

Humidification should be considered for all cold climates. The HVAC designer must also consider avoiding coil freeze up in water based systems. Chapters 31 and 44 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment* provide information about makeup air units and air-to-air energy recovery, respectively.

Hotel location, environmental quality desired by the owner, and design sophistication determines the system selected. For example, in locations with cool summers, dehumidification with mechanical cooling only is satisfactory. For humid locations or where enhanced dehumidification is required, a desiccant-based unit can provide lower supply air humidity, to help prevent mold and mildew and provide internal latent cooling.

Central Mechanical Plant. Designing a reliable and energy-efficient mechanical plant is essential to ensuring a profitable hotel. The chiller plant must operate efficiently at part-load conditions. Some redundancy should be considered in case of equipment failure. Designs often include spare critical equipment where spare parts and qualified service are not readily available. Chillers with multistage compressors should be considered because they provide partial cooling during failures and enhance part-load operation. When using two chillers, each should provide at least 60% of the total load. Combinations of three chillers providing 40% each or four chillers providing 30% each are better for tracking part-load conditions. Cooling towers, pumps, etc., can be sized in a similar manner.

The heating plant should be designed to accommodate the winter heating load and could provide domestic hot water, swimming pool heating, and service to kitchens and laundries as well. The type of fuel used depends on location, availability, use, and cost.

Multipurpose boiler design for the kitchen and laundry should offer redundancy, effective part-load handling, and efficient operation during summer, when the HVAC heating load does not exist.

In areas with mild winters, a two-pipe system or an air-to-water heat pump chiller/heater can be considered. In any event, the HVAC designer must understand the need for all-year cooling and heating availability in the public areas. In this case, a combination of air-to-water heat pump, chiller/heater for the guest rooms, and independent heat pumps for public areas can be installed.

Acoustics and Noise Control. The sound level in guest room and public areas is a major design element. Both the level and constancy of noise generated by the HVAC unit are of concern. Normally, packaged terminal air conditioners/heat pumps and water-source heat pumps are noisier because of the compressor. Some equipment, however, has extra sound insulation, which reduces the noise significantly.

Lowering fan speed, which is usually acceptable, can reduce fan noise levels. On/off cycling of the fan and compressor can be objectionable, even if the generated noise is low. Temperature con-

trol by cycling the fan only (no flow control valve) should not be used.

Another source of noise is sound that transfers between guest rooms through the toilet exhaust duct. Internal duct lining and sound attenuators are commonly used to minimize this problem.

Noise from equipment located on the roof or in a mechanical room located next to a guest room should be avoided. Proper selection of vibration isolators should prevent vibration transmission. In critical cases, an acoustician must be consulted.

New Technology in Hotels. Modern hotels are implementing new techniques to enhance comfort and convenience. For example, the telephone, radio, TV, communications, lighting, and air-conditioning unit can be integrated into one control system. Occupancy sensors conserve energy by resetting the temperature control when the room is occupied or when guests leave. As soon as a new guest checks in at the front desk, the room temperature is automatically reset. But even with this improved technology, it is important to remember that temperature reset may create humidity problems.

DORMITORIES

Dormitory buildings frequently have large commercial dining and kitchen facilities, laundering facilities, and common areas for indoor recreation and bathing. These ancillary loads may make heat pump or total energy systems appropriate, economical alternatives, especially on campuses with year-round activity.

When dormitories are shut down during cold weather, the heating system must supply enough heat to prevent freezing. If the dormitory contains non-dwelling areas such as administrative offices or eating facilities, these facilities should be designed as a separate zone or with a separate system for flexibility, economy, and odor control.

Subsidiary facilities should be controlled separately for flexibility and shutoff capability, but they may share common refrigeration and heating plants. With internal-source heat pumps, this interdependence of unitary systems allows reclamation of all internal heat usable for building heating, domestic water preheating, and snow melting. It is easier and less expensive to place heat reclaim coils in the building's exhaust than to use air-to-air heat recovery devices. Heat reclaim can easily be sequence controlled to add heat to the building's chilled-water system when required.

MULTIPLE-USE COMPLEXES

Multiple-use complexes combine retail, office, hotel, residential, and/or other commercial spaces into a single site. Peak HVAC demands of the various facilities may occur at different times of the day and year. Loads should be determined independently for each occupancy. Where a central plant is considered, a block load should also be determined.

Separate air handling and distribution should serve separate facilities. However, heating and cooling units can be combined economically into a central plant. A central plant provides good opportunities for heat recovery, thermal storage, and other techniques that may not be economical in a single-use facility. A multiple-use complex is a good candidate for central fire and smoke control, security, remote monitoring, billing for central facility use, maintenance control, building operations control, and energy management.

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CHAPTER 6

EDUCATIONAL FACILITIES

THIS chapter contains technical, environmental, and design considerations to assist the design engineer in the proper application of heating, ventilation, and air-conditioning systems and equipment for educational facilities.

PRESCHOOLS

General Design Considerations

Commercially operated preschools are generally provided with standard architectural layouts based on owner-furnished designs. A typical preschool facility provides programs for infants (1 to 2 years old), toddlers (2 years old), and preschoolers (3 to 4 years old). Larger facilities also offer programs for older children, such as kindergarten programs (5 years old). Areas such as lobbies, libraries, and kitchens are also included to support the variety of programs. Given this range of age, special attention for the design of the HVAC systems is required to meet the needs of every age group.

All preschool facilities require quiet and economical systems. The equipment should be easy to operate and maintain, and the design should provide warm floors and no drafts. These facilities have two distinct occupant zones: (1) the floor level, where younger children play, and (2) normal adult height, for the teachers. The teacher also requires a place for a desk; consider treating this area as a separate zone.

Preschool facilities generally operate on weekdays from early in the morning to 6:00 or 7:00 PM. This schedule usually coincides with the normal working hours of the children's parents plus one

hour for drop-off and pick-up. The HVAC systems therefore operate 12 to 14 h per workday, and may be either off or on at night and weekends, depending on whether setback is applied.

Supply air outlets should be positioned so that the floor area is maintained at about 75°F without the introduction of drafts. Both supply and return air outlets should be placed where they will not be blocked by furniture positioned along the walls or where children can reach them. Coordination with the architect about locating these outlets is essential. Proper ventilation is crucial for controlling odors and helping prevent spread of diseases among the children.

Floor-mounted heating equipment, such as electric baseboards heaters, should be avoided because children must be prevented from coming in contact with hot surfaces or electrical devices. However, radiant-floor systems can be used safely and effectively.

Design Criteria

Table 1 provides typical indoor design conditions for preschools. Table 2 provides typical ventilation and exhaust design criteria using the ventilation rate procedure of ANSI/ASHRAE *Standard* 62.1-2004; the user's manual (ASHRAE 2004a) is also

Table 1 Recommended Temperature and Humidity Design Criteria for Various Spaces in Preschools

Category/Humidity Criteria	Indoor Design Conditions, °F	
	Winter	**Summer**
Infant, Toddler, and Preschooler Classrooms[a]		
30% rh	68.5 to 75.5	74.0 to 80.0
40% rh	68.0 to 75.0	73.5 to 80.0
50% rh	68.5 to 74.5	73.0 to 79.0
60% rh	67.5 to 74.0	73.0 to 78.5
Administrative, Offices, Lobby, Kitchen		
30 to 60% rh	68.5 to 74.0	74.0 to 78.5
Storage		
No humidity control	64.0	
Mechanical Rooms[b]		
No humidity control	61.0	

Notes:
[a]Based on EPA (2000) and ASHRAE *Standard* 55-2004 for people wearing typical summer and winter clothing, at mainly sedentary activity.
[b]Usually not conditioned.

Table 2 Typical Recommended Design Criteria for Ventilation and Filtration for Preschools

	Ventilation and Exhaust [a, g, j]				Minimum Filtration Efficiency, MERV[h]
	Outdoor Air, cfm/ Person	Occupant Density[k] per 1000 ft²	Outdoor Air		
Category			cfm/ft²	cfm/Unit	
Infant, Toddler, and Preschooler Classrooms[b]	17	25			6 to 8
Administrative and Office Space[c]	17	5			6 to 8
Kitchen[d]			0.3 (exhaust)		[i]
Toilets[e]				50 (exhaust)	NA
Storage[f]			0.12		1 to 4

Notes:
[a]Based on ANSI/ASHRAE *Standard* 62.1-2004, Table 6-1, default values for ventilation, and Table 6-4 for exhaust rates.
[b]Based on ASHRAE *Standard* 62.1-2004, Table 6-1, default values for educational facilities-daycare.
[c]Based on ASHRAE *Standard* 62.1-2004, Table 6-1, default values for office buildings/office spaces.
[d]Based on ASHRAE *Standard* 62.1-2004, Table 6-4, for kitchenettes.
[e]Based on ASHRAE *Standard* 62.1-2004, Table 6-4, for private toilets (rate is for toilet room intended to be occupied by one person).
[f]Based on ASHRAE *Standard* 62.1-2004, Table 6-1, for storage rooms.
[g]This table should not be used as the only source for design criteria. Governing local codes, design guidelines, and ASHRAE *Standard* 62.1-2004 with current addenda *must* be consulted.
[h]MERV = minimum efficiency reporting values, based on ASHRAE *Standard* 52.2-1999.
[i]See Chapter 31 for additional information on kitchen ventilation.
[j]Consult local codes for exhaust requirements.
[k]Use default occupancy density when actual occupant density is not known.

The preparation of this chapter is assigned to TC 9.7, Educational Facilities.

Table 3   Typical Recommended Design Guidelines for HVAC: Related Background Sound for Preschool Facilities

Category	Sound Criteria[a, b] RC (N); QAI < 5 dB	Comments
Infant, Toddler, and Preschooler Classrooms	25 to 30	
Administrative/Office Areas	30 to 40	For open-plan office
Service/Support Areas	35 to 45	

Notes:
[a]Based on Chapter 47.
[b]RC (Room Criterion), QAI (Quality Assessment Index) from Chapter 7 of 2005 *ASHRAE Handbook—Fundamentals*.

strongly recommended for additional information on applying this standard. Table 3 lists design criteria for acceptable noise in preschool facilities.

Load Characteristics

Preschool cooling and heating loads depend heavily on ambient conditions, because the rooms typically have exterior exposures (walls, windows, and roofs) and also relatively higher needs for ventilation. Although preschool facilities are relatively small, the design engineer must pay special attention to properly calculate the cooling, heating, dehumidification, and humidification loads. Sizing and applying the HVAC equipment is critical for handling the loads and the large amounts of outdoor air from a capacity and occurrence standpoint (peak sensible and latent loads do not always coincide).

Humidity Control

Preschool classrooms require humidity control to provide human comfort and prevent health problems. Maintaining humidity levels between 30 and 60°F dew point satisfies nearly all people nearly all the time. However, the designer should discuss comfort expectations with the owner, to avoid misunderstandings.

In hot and humid climates, it is recommended that air conditioning and/or dehumidification be operated year-round to prevent growth of mold and mildew. Dehumidification can be improved by adding optional condenser heat/reheat coils, heat pipes, or air-to-air heat exchangers in conjunction with humidity sensors in the conditioned space or return air. Additional information on humidity control is in the section on K-12 Schools.

Systems and Equipment Selection

HVAC systems for preschools are typically decentralized, using either self-contained or split air-conditioners or heat pumps (typically air- or water-source). When the preschool is part of a larger facility, utilities such as chilled water, hot water, or steam from a central plant can be used. When natural gas is available, the heating system can be a gas-fired furnace, or, when economically justifiable, electric heat can be used.

The type of HVAC equipment selected also depends on the climate and the months of operation. In hot and dry climates, for instance, evaporative cooling may be the primary type of cooling. In colder climates, heating can also be provided by a hot-water hydronic system originating from a boiler plant in conjunction with radiant floor or hot-water coils.

Decentralized systems are dedicated systems serving a single zone, and typically include the following:

- Direct-expansion (DX) split systems
- Rooftop packaged air conditioners or heat pumps with or without optional enhanced dehumidification (condenser reheat coil)
- Rooftop packaged air conditioners or heat pumps integrated with an energy recovery module, with optional enhanced dehumidification (condenser reheat coil; see Figure 1)
- Water-source heat pumps (with cooling tower and supplementary boiler)

Table 4   Applicability of Systems to Typical Areas[d]

Typical Area	Decentralized Cooling/Heating Systems[c]				Heating Only
	PSZ/ SZ Split	PSZ with Energy Recovery and Dehumidification	WSHP	Geothermal Heat Pump	Radiant Floor [b]
Classrooms	X[a]	X[a]	X	X	X
Administrative Areas, Lobby	X		X	X	
Kitchen	X		X	X	
Ventilation (Outdoor Air)	DOAS		DOAS	DOAS	DOAS

SZ = single zone   PSZ = packaged single zone
WSHP = water-source heat pump   DOAS = dedicated outdoor air system
Notes:
[a]PSZ for classrooms requires individual thermostatic control.
[b]Typically with cooling system such as PSZ/SZ split.
[c]Heating system for PSZ/SZ split can be gas furnace, hot-water coil, or electric.
[d]See Table 11 for additional systems if preschool is not a stand-alone facility.

- Geothermal heat pumps (ground-coupled, ground-water-source, surface-water-source)
- Packaged dedicated outdoor air systems (DOAS) with DX system for cooling and gas-fired furnace, electric heating, or part of water-source and geothermal heat pump system

Information about decentralized systems can be found in Chapters 5 and 45 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*. Additional information on geothermal heat pumps can be found in Kavanaugh and Rafferty (1997) and Chapter 32 of this volume. Chapter 6 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment* provides information on radiant heating.

Note that some decentralized systems may need additional acoustical modifications to meet the design criteria in Table 3. Therefore, it is strongly recommended to carefully check the acoustical implications of applying these systems.

Dedicated Outdoor Air Systems (DOAS). Specialized dedicated outdoor air systems (DOAS) should be used to treat outdoor air before it is introduced into classrooms or other areas. DOAS units can bring 100% outdoor air to at least space conditions, which allows the individual space units to handle only the space cooling and heating loads. A detailed description of DOAS is shown in the K-12 Schools section of this chapter. Additional information can be found in Chapter 47 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*.

Systems Selection by Application. Table 4 shows the applicability of systems to areas in preschool facilities.

Energy Considerations

Energy standards such as ANSI/ASHRAE/IESNA *Standard* 90.1-2004 and local energy codes should be followed for minimum energy conservation criteria. Additional energy conservation measures include the following:

- **Energy management systems (EMS)** and **direct digital control (DDC)** for easier maintainability of comfort conditions, optimized operation, troubleshooting, and monitoring
- **Temperature night/weekends setback** (winter) or **setup** (summer) by central EMS or stand-alone programmable thermostats
- **Morning warm-up** (winter) or **cooldown** (summer), typically by the central EMS
- **Ventilation control**, by throttling the space outdoor air damper to minimum position or close during unoccupied hours
- **Air-to-air energy recovery** for ventilation or in conjunction with the HVAC unit
- **Enhanced summer humidity control** by switching DOAS from 100% outdoor air to 100% recirculation and maintaining required summer humidity dew-point temperature
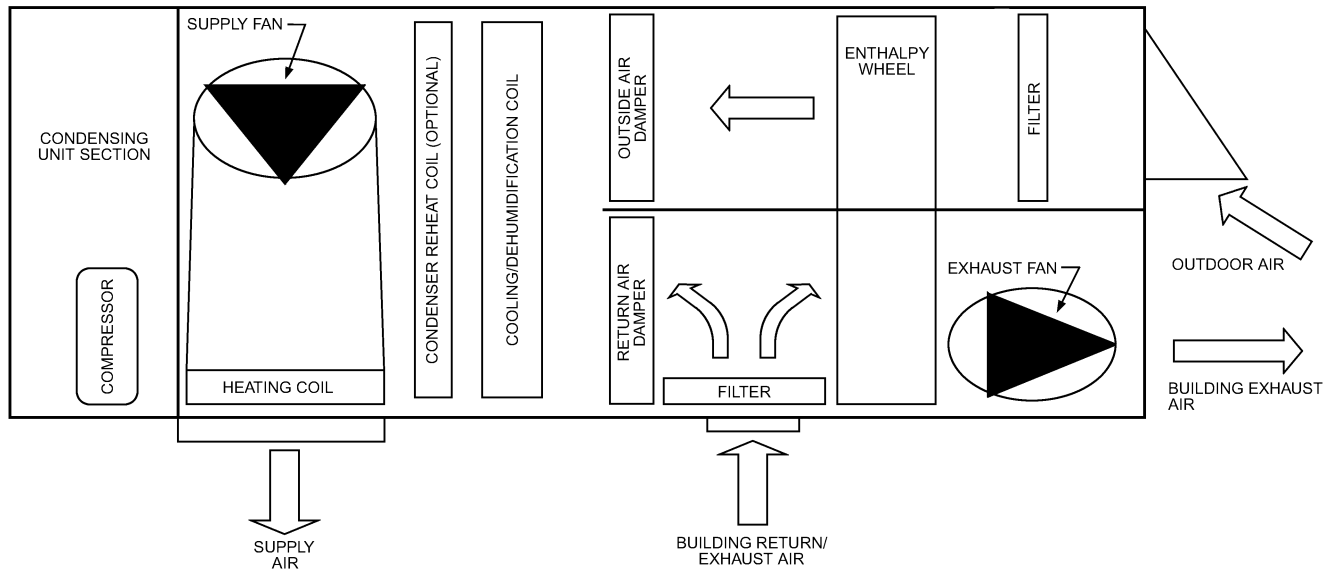
Fig. 1   Typical Configuration of Rooftop Packaged Air Conditioners with Energy Recovery Module and Enhanced Dehumidification (Condenser Reheat Coil)

- **Evaporative cooling systems**, where weather conditions permit
- **Natural ventilation**, when applicable, by using operable windows
- **Passive heating and cooling** techniques, in cooperation with the architect
- **Solar heating**, when economically justifiable for domestic hot-water heating and space heating

K-12 SCHOOLS

General and Design Considerations

K (kindergarten)-12 schools typically include elementary, middle, and high schools. These facilities are typically one- to three-story buildings.

Elementary schools are generally comprised of 10 to 15 classrooms plus cafeteria, administration, gymnasium, and library areas. Elementary schools are typically used during the school season (late August to June); during summer, they are typically closed or have minimal activity. Current trends include science classrooms and a preschool facility. Typical elementary schools operate between 7:00 AM and 4:00 PM.

Middle schools are larger than elementary schools and include additional computer classrooms and locker rooms. Their hours of operation are longer because of extracurricular activities. A recent trend toward eliminating middle schools (retaining traditional K-8 elementary and 9-12 high schools) (Wright 2003) may require that elementary school designs incorporate some middle school features.

High schools also include a cafeteria and auditorium, and may include a natatorium, ice-skating rink, etc. High schools operate longer hours and are often open during the summer, either as a summer school or to use special facilities such as gymnasiums, natatoriums, etc.

Typical areas found in K-12 schools are shown in Table 5.

K-12 schools require an efficiently controlled atmosphere for a proper learning environment. This involves the selection of heating, ventilation, and air-conditioning systems, equipment, and controls to provide adequate ventilation and indoor air quality (IAQ), comfort, and a quiet atmosphere. The system must also be easily maintained by the facility's maintenance staff.

The following are general design considerations for each of the areas typically found in K-12 schools:

Table 5   Typical Spaces in K-12 Schools

Typical Area	School		
	Elementary (K to 5)[a]	Middle (6 to 8)[a]	High (9 to 12)[a]
Classrooms	X	X	X
Science	X	X	X
Computer	X	X	X
Laboratories and Science Facilities		X	X
Administrative Areas	X	X	X
Gymnasium	X	X	X
Libraries	X	X	X
Auditorium			X
Home Economics Room			X
Cafeteria	X	X	X
Kitchen	X	X	X
Auto Repair Shop[b]			X
Industrial Shop			X
Locker Rooms		X	X
Ice Rink[b]			X
Natatorium[b]			X
School Store[b]			X

Notes: [a]School grades can vary. [b]These zones are not typical.

Classrooms. Classrooms typically range between 900 and 1000 ft^2, and are typically designed for 20 to 30 students. Each classroom should be, at a minimum, heated and ventilated. Air conditioning should be seriously considered for school districts that have year-round classes in warm, humid climates. In humid climates, seriously consider providing dehumidification during summer, even if the school is unoccupied, to prevent mold and mildew.

Science Classrooms. Science rooms are now being provided for elementary schools. Although the children do not usually perform experiments, odors may be generated if the teacher demonstrates an experiment or if animals are kept in the classroom. Under these conditions, adequate ventilation is essential along with an exhaust fan with a local on/off switch for occasional removal of excessive odors.

Computer Classrooms. These rooms have a high sensible heat load because of the computer equipment. They may require additional cooling equipment such as small spot-cooling units to offset the additional load. Humidification may also be required. See Chapter 17 for additional information.

Educational Laboratories. Middle and secondary school laboratories and science facilities may require fume hoods with special exhaust systems. A makeup air system may be required if there are several fume hoods within a room. If there are no fume hoods, a room exhaust system is recommended for odor removal, depending on the type of experiments conducted in the room and whether animals are kept within the room. Associated storage and preparation rooms are generally exhausted continuously to remove odors and vapors emanating from stored materials. The amount of exhaust and the location of exhaust grilles may be dictated by local codes or National Fire Protection Association (NFPA) standards. See Chapter 14 for further information. Additional information on laboratories can be found in McIntosh et al. (2001) and ANSI/AIHA *Standard* Z9.5-2003.

Administrative Areas. The office area should be set up for individual control because it is usually occupied during and after school hours. Because offices are also occupied before school starts in the fall, air conditioning for the area should be considered or provisions should be allowed for future upgrades.

Gymnasiums. Gyms may be used after regular school hours for evening classes, meetings, and other functions. The gym may also be used on weekends for group activities. The loads for these occasional uses should be considered when selecting and sizing the systems and equipment. Independent gymnasium HVAC systems with control capability allow for flexibility with smaller part-load conditions. If a wooden floor is installed, humidity control should be considered to avoid costly damage.

Libraries. Libraries should be air-conditioned to preserve the books and materials stored in them. See Chapters 3 and 21 for additional information.

Auditoriums. These facilities require a quiet atmosphere as well as heating, ventilation, and, in some cases, air conditioning. Auditoriums are not often used, except for assemblies, practice for programs, and special events. For other considerations, see Chapter 4.

Home Economics Rooms. These rooms usually have a high sensible heat load from appliances such as washing machines, dryers, stoves, ovens, and sewing machines. Different options should be considered for exhaust of stoves and dryers. If local codes allow, residential-style range hoods may be installed over the stoves. A central exhaust system could be applied to the dryers as well as to the stoves. If enough appliances are located within the room, a makeup air system may be required. These areas should be maintained at negative pressure in relation to adjacent classrooms and administrative areas. See Chapter 31 for more information.

Cafeteria and Kitchen. Typical schools requires space for preparation and serving of meals. A well-designed school cafeteria includes the following areas: loading/receiving, storage, kitchen, serving area, dining area, dishwashing, office, and staff facilities (lockers, lavatories, and toilets). Chapter 3 provides detailed information on design criteria, load characteristics, and design concepts for these facilities.

Auto Repair Shops. These facilities require outdoor air ventilation to remove odors and fumes and to provide makeup air for exhaust systems. The shop is usually heated and ventilated but not air-conditioned. To contain odors and fumes, return air should not be supplied to other spaces, and the shop should be kept at a negative pressure relative to the surrounding spaces. Special exhaust systems such as welding exhaust or direct-connected carbon monoxide exhaust systems may be required. See Chapter 30 for more information.

Industrial Shops. These facilities are similar to auto repair shops and have special exhaust requirements for welding, soldering, and paint booths. In addition, a dust collection system is sometimes provided and the collected air is returned to the space. Industrial shops have a high sensible load from operation of the shop equipment. When calculating loads, the design engineer should consult the teacher about shop operation, and, where possible, diversity factors should be applied. See Chapter 30 for more information.

Locker Rooms. Building codes in the United States require that these facilities be exhausted directly to the outside when they contain toilets and/or showers. They are usually heated and ventilated only. These areas typically require makeup air and exhaust systems that should operate only when required.

Ice Rinks. These facilities require special HVAC and dehumidification systems to keep spectators comfortable, and to prevent roof condensation and fog formation at the surface. See Chapter 4 of this volume, Chapter 34 of the 2006 *ASHRAE Handbook—Refrigeration*, and Harriman et al. (2001) for more on these systems.

Natatoriums. These facilities, like ice rinks, require special humidity control systems. In addition, special construction materials are required. See Chapter 4 and Harriman et al. (2001) for more on these systems.

School Stores. These facilities contain school supplies and paraphernalia and are usually open for short periods of time. The heating and air-conditioning systems serving these areas should be able to be shut off when the store is closed to save energy.

Design Criteria

A typical HVAC design criteria covers parameters required for thermal comfort, indoor air quality (IAQ), and sound. Thermal comfort parameters (temperature and humidity) are well covered by ANSI/ASHRAE *Standard* 55-2004 and Chapter 8 of the 2005 *ASHRAE Handbook—Fundamentals*. Ventilation and IAQ are covered by ANSI/ASHRAE *Standard* 62.1-2004, the user manual for that standard (ASHRAE 2004), and Chapter 27 of the 2005 *ASHRAE Handbook—Fundamentals*. Sound and vibration are discussed in Chapter 47 of this volume and Chapter 7 of the 2005 *ASHRAE Handbook—Fundamentals*.

Thermal comfort is affected by air temperature, humidity, air velocity, and mean radiant temperature (MRT). In addition, non-environmental factors (clothing, gender, age, and physical activity). affect thermal comfort. These variables and how they correlate to the thermal comfort can be evaluated by the *Thermal Comfort Tool CD* (ASHRAE 1997) in conjunction with ANSI/ASHRAE *Standard* 55-2004. It is important to indicate that, in addition to thermal comfort criteria, several zones in schools (libraries, gymnasiums, locker rooms, natatoriums, ice rinks, etc.) require additional considerations to cover issues such as mold prevention, condensation, corrosion, etc., as discussed in more detail in the section on Humidity Control. General guidelines for temperature and humidity applicable for K-12 schools are shown in Table 6.

All schools need outdoor air for ventilation. Outdoor air is introduced to occupied areas and then exhausted by fans or exhaust openings, removing indoor air pollutants generated by occupants and any other building-related sources. ANSI/ASHRAE *Standard* 62.1-2004 is used as the basis for many building codes. To define the ventilation and exhaust design criteria, consult local applicable ventilation and exhaust standards. Table 7 provides recommendations for ventilation design based on the ventilation rate procedure method and filtration criteria for K-12 educational facilities.

Additional information on IAQ for educational facilities can be found in EPA (2000).

Acceptable noise levels in classrooms are critical for a proper learning environment. High noise levels reduce speech intelligibility and student's learning capability. Although Chapter 47 provides information on design noise criteria, additional sources, such as local codes and ANSI *Standard* S12.60-2002, should be consulted for adequate design criteria. Table 8 summarizes applicable noise criteria for K-12 schools.

Load Characteristics

Proper cooling, heating, dehumidification, and humidification load calculations and properly sized equipment are critical to both energy efficiency and cost effectiveness. Many computer programs and calculation methodologies, as described in Chapter 30 of the

Table 6   Typical Recommended Temperature and Humidity Ranges for K-12 Schools

| | Indoor Design Conditions | | |
| | Temperature, °F | | |
Category/Humidity Criteria	Winter	Summer	Comments
Classrooms, Laboratories, Libraries, Auditoriums, Offices [a, e]			
30% rh	68.5 to 75.5	74.0 to 80.0	
40% rh	68.0 to 75.0	73.5 to 80.0	
50% rh	68.5 to 74.5	73.0 to 79.0	
60% rh	67.5 to 74.0	73.0 to 78.5	
Gymnasiums			
30 to 60% rh	68.5 to 74.0	74.0 to 78.5	For gym with wooden floor, 35 to 50% humidity recommended at all times
Shops			
20 to 60% rh	68.5 to 74.0	74.0 to 78.5	
Cafeteria[b]			
20 to 30% (winter), 50% (summer) rh	70.0 to 73.5	78.5	
Kitchen[b]			
No humidity control	70.0 to 73.5	84.0 to 88.0	
Locker/Shower Rooms			
No humidity control	75.0		Usually not conditioned
Toilets			
No humidity control	72.0		Usually not conditioned
Storage			
No humidity control	64.0		
Mechanical Rooms			
No humidity control	61.0		Usually not conditioned
Corridors			
No humidity control	68.0		Frequently not conditioned
Natatorium[c]			
50 to 60% rh	75.0 to 84.0	75.0 to 84.0	Based on recreational pool
Ice Rink[d]			
35 to 45°F dp (maximum)	50.0 (minimum)	65.0 (maximum)	Minimum 10°F temperature difference between dew point and dry bulb to prevent fog and condensation

Notes:
[a]Based on EPA (2000) for people wearing typical summer and winter clothing, at mainly sedentary activity.
[b]Based on Chapter 3.
[c]Based on Chapter 4.
[d]Based on Harriman et al. (2001).
[e]For libraries, keep minimum humidity of 30°F dp and maximum of 55% rh.

2005 *ASHRAE Handbook—Fundamentals*, can be used for these tasks. Assumptions and data used about infiltration, lighting, equipment loads, occupancy, etc., are critical for proper load calculations. Although equipment is sized by peak cooling and heating, it is extremely important to analyze the occurrences of the peak sensible and latent cooling loads. In many instances, peak sensible cooling load does not coincide with peak latent cooling load. Ignoring this phenomenon can result in unacceptable indoor humidity. By carefully analyzing and understanding the peak loads and the load profiles, the designer can properly apply and size the most suitable equipment to meet the sensible and the latent cooling loads efficiently. Elementary schools are generally occupied from about 7:00 AM to about 3:00 PM; occupation is longer for middle and high schools. Peak cooling loads usually occur at the end of the school day. Peak heating usually occurs early in the day, when classrooms begin to be occupied and outdoor air is introduced into the facility. Although K-12 schools are dominated by perimeter zones (and zones exposed to the roof), careful attention should be given to components of the loads. Typical breakdowns of moisture loads are shown in Table 9.

Typically, the dominant cooling loads in classrooms are occupants and ventilation, and ventilation and roof for heating. Given the dominance of ventilation loads, special effort should be made to effectively treat outdoor air before its introduction to the space, as discussed in more detail in the section on Systems and Equipment Selection.

Humidity Control

School buildings host many activities that require special humidity control. Harriman et al. (2001) provide detailed information on the basics of design and equipment selection for proper humidity control for several applications; Chapter 18 is dedicated to schools.

Classrooms require humidity control to provide comfort and prevent humidity-related problems (e.g., growth of dust mites and fungus, which produce allergens and even toxic by-products). Low humidity, on the other hand, favors longevity of infectious viruses, and therefore their transmission between occupants. Maintaining dew point levels between 30 and 60°F satisfies nearly all people nearly all the time. However, the designer should discuss comfort expectations with the owner, to avoid misunderstandings.

Libraries require humidity control to provide human comfort to the occupants and also to protect books and electronic records. Maintaining dew point levels between 30 and 60°F provides a comfortable environment for the library occupants. However, controlling humidity at this range does not prevent books from absorbing excess moisture. Typically, books take up moisture quickly but lose it slowly. To avoid growth of mold and mildew, a dew point above 30°F and maximum of 55% rh are recommended. As for classrooms, the principal moisture loads for the library are ventilation (the major load) and infiltration.

Gymnasiums with wooden floors require special attention; failure to control humidity in gyms with wooden floors may have costly

Table 7 Typical Recommended Design Criteria for Ventilation and Filtration for K-12 Schools

Category	Combined Outdoor Air, cfm/Person	Occupant Density,[i] per 1000 ft²	Outdoor Air cfm/ft²	Outdoor Air cfm/Unit	Minimum Filtration Efficiency, MERV[c]
Classrooms, Ages 5 to 8	15	25			6 to 8
Ages 9 and over	13	35			6 to 8
Lecture	8	65			6 to 8
Art	19	20			6 to 8
Lecture Halls (fixed seats)	8	150			6 to 8
Science Laboratories[f]	17	25			6 to 8
Computer Lab	15	25			6 to 8
Media Center	15	25			6 to 8
Music/Theatre/Dance	12	35			6 to 8
Multiuse Assembly	8	100			6 to 8
Libraries	17	10			6 to 8
Auditorium	5	150			9 to 10[g]
Administrative/Office Areas	17	5			6 to 8
Gymnasium (playing floors)			0.3		6 to 8
Wood/Metal Shops	19	20			6 to 8
Locker Rooms			0.5 (exhaust)		1 to 4
Cafeteria	9	100			6 to 8
Kitchen[d, e]			0.7 (exhaust)		NA
Toilets				70 (exhaust)	NA
Storage			0.12		1 to 4
Corridors			0.06		6 to 8
Natatoriums (pool and deck)			0.48		6 to 8
Ice Rinks (spectator areas)[h]	8	150			6 to 8

Notes:
[a]Based on ANSI/ASHRAE *Standard* 62.1-2004, Tables 6-1 and 6-4. For systems serving multiple zones, apply multiple zone calculations procedure. See the section on Demand Control Ventilation (DCV) when DCV is considered.
[b]This table should not be used as the only source for design criteria. Governing local codes, design guidelines, ANSI/ASHRAE *Standard* 62.1-2004 and user's manual (ASHRAE 2004a) *must* be consulted.
[c]MERV = minimum efficiency reporting values, based on ASHRAE *Standard* 52.2-1999.
[d]See Chapter 31 for additional information on kitchen ventilation.
[e]Consult local codes for kitchen exhaust requirements.
[f]This table should not be used as the only source for laboratory design criteria. Governing local codes and design guidelines such as ANSI/AIHA *Standard* Z9.5-2003 and Chapter 14 of this volume *must* be consulted.
[g]When higher filtration efficiency specified, prefiltration is recommended.
[h]Based on ANSI/ASHRAE *Standard* 62.1-2004 values for sports and entertainment; for rink playing area, use gymnasium (playing floors) design criteria. Special attention should be given to internal-combustion ice-surfacing equipment for carbon monoxide control. Consult local code for ice rink design.
[i]Use default occupancy density when actual occupant density is not known.

Table 8 Typical Recommended Design Guidelines for HVAC-Related Background Sound for K-12 Schools

Category	Sound Criteria[a, b] RC (N); QAI < 5 dB	Comments
Classrooms	25 to 30	
Large Lecture Rooms	25 to 30	
Without speech amplification	25	
Science Laboratories	35 to 45	
Libraries	30 to 40	See Table 42 of Chapter 47
Auditorium	30 to 35	Use as guide only; consult acoustician
Administrative	30 to 40	For open-office space
Gymnasium	40 to 50	
Shops	35 to 45	Use as guide only; consult acoustician
Cafeteria	35 to 45	Based on service/support for hotels
Kitchen	35 to 45	Based on service/support for hotels
Storage	35 to 45	
Mechanical Rooms	35 to 45	
Corridors	35 to 45	
Natatoriums	40 to 50	
Ice Rinks	40 to 50	Based on values for gymnasiums and natatoriums

Notes:
[a]Based on Chapter 47.
[b]RC (Room Criterion), QAI (Quality Assessment Index) from Chapter 7 of the 2005 *ASHRAE Handbook—Fundamentals*.

Table 9 Typical Classroom Summer Latent (Moisture) Loads

Category	Moisture Loads, lb/h	Moisture Loads, %
People	7.3	22.5
Permeance	0.2	0.6
Ventilation	20.3	62.5
Infiltration	4.7	14.4
Doors	0	0
Wet Surfaces	0	0
Humid Materials	0	0
Domestic Loads	0	0

Note: Based on Harriman et al. (2001), Chapter 18, Figure 18.2.

consequences. The Maple Flooring Manufacturers Association (MFMA) specifies a floor-level humidity between 35 and 50% rh.

Showers and **locker rooms** require humidity control to prevent corrosion and growth of bacteria and fungus. Therefore, special attention is required to exhaust air quantities and placement of supply and exhaust air registers.

Natatoriums and **ice rinks** are typically isolated areas with more specialized HVAC equipment specifically designed to address ventilation and humidity control. Chapters 27 and 28 of Harriman et al. (2001) provide detailed information on humidity control for natatoriums and ice rinks, respectively.

Systems and Equipment Selection

Selection of HVAC equipment and systems depends on whether the facility is new or existing, and whether it is to be totally or partially renovated. For minor renovations, existing HVAC systems are often expanded in compliance with current codes and standards with equipment that matches the existing types. For major renovations or new construction, new HVAC systems and equipment

should be installed. When applicable, the remaining useful life of existing equipment and distribution systems should be considered.

HVAC systems and equipment energy use and associated life cycle costs should be evaluated. Energy analysis may justify new HVAC equipment and systems when an acceptable return on investment can be shown. The engineer must review all the assumptions in the energy analysis with the school administration. Assumptions, especially about hard-to-measure items such as infiltration and part-load factors, can significantly affect the energy use calculated.

Other considerations for existing facilities are (1) whether the central plant is of adequate capacity to handle additional loads from new or renovated facilities; (2) the age and condition of the existing equipment, pipes, and controls; and (3) the capital and operating costs of new equipment. Schools usually have very limited budgets. Any savings in capital expenditures and energy costs may be available for the maintenance and upkeep of the HVAC systems and equipment and for other facility needs.

The type of HVAC equipment selected also depends on the climate and months of operations. In hot, dry climates, for instance, evaporative cooling may be the primary approach. Some school districts may choose not to provide air conditioning. However, in hot, humid climates, it is recommended that air conditioning or dehumidification be operated year-round to prevent growth of mold or mildew.

Chapter 1 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment* provides general guidelines on HVAC systems analysis and selection procedures. Although in many cases system selection is based solely on the lowest first cost, it is suggested that the engineer propose a system with the lowest life-cycle cost (LCC). LCC analysis typically requires hour-by-hour building energy simulation for annual energy cost estimation. Detailed initial and maintenance cost estimates of proposed design alternatives, using sources such as R.S. Means (R.S. Means 2007a, 2007b), can also be used for the LCC analysis along with software such as BLCC 5.1 (FEMP 2003). See Chapter 36 for additional information.

System Types. HVAC systems for K-12 schools may be centralized, decentralized, or a combination of both. Centralized systems typically incorporate secondary systems to treat the air and distribute it. The cooling and heating medium is typically water or brine that is cooled and/or heated in a primary system and distributed to the secondary systems. Centralized systems comprise the following systems:

Secondary Systems

- Building air distribution systems (see Chapter 2 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*)
- Fan-coil systems (see Chapter 3 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*)
- Dedicated outdoor air systems (DOAS) with chilled water for cooling and hot water, steam, or electric heat for heating

Primary Systems

- Central cooling and heating plant (see Chapter 4 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*)

More detailed information on systems selection by application can be found in Table 11.

Typical decentralized systems (dedicated systems serving a single zone) are discussed in the section on Preschools under Systems and Equipment Selection.

It is important to note that, to meet the acoustical design criteria in Table 8, designers should avoid locating HVAC equipment in classrooms, and that some centralized and decentralized systems located close to classrooms might need additional sound-attenuating features. Coordination between the HVAC designer, architect, and acoustical consultant is critical for meeting the desired noise criteria. Siebein and Likendey (2004) provides information on the applicability of

systems to classrooms with regard to acoustical criteria. Additional information on how HVAC&R manufacturers' acoustical data and application information can be best used can be found in Ebbing and Blazier (1998). Schaffer (1993) provides a practical guide to noise and vibration control for HVAC systems. Commercial acoustics analysis software can also be helpful.

Dedicated Outdoor Air Systems (DOAS). Although most centralized and decentralized systems are very effective at handling the space sensible cooling and heating loads, they are less effective (or ineffective) at handling ventilation air and the latent loads. As a result, a dedicated outdoor air system (DOAS) should be used. DOAS units bring 100% outdoor air to at least space conditions, which allows individual space units to handle only the space loads. It is preferable, however, to introduce the outdoor air at a lower humidity ratio than the desired space humidity ratio, to allow the zone HVAC unit to handle only the space sensible cooling load. This approach can be easily implemented in a classroom where a significant amount of outdoor air is required for ventilation.

Example. In a typical classroom with 30 students, the ventilation requirements are 450 cfm. If the outdoor air can be introduced at a humidity ratio of 48 gr/lb and the space is designed to be maintained at 70 gr/lb, the space dehumidification capability of the pre-dehumidified outdoor air is the following:

$$\text{Space dehumidification capability, Btu/h} = 0.68 \times \text{cfm} \times \left(\begin{array}{c} \text{Space humidity ratio} - \\ \text{Supply humidity ratio} \end{array} \right)$$

Then,

$$\text{Dehumidification capability, Btu/h} = 0.68 \times 450 \times (70 - 48) = 6732 \text{ Btu/h}$$

where

$$0.68 = (60/13.5)(1076/7000)$$

- 60 = min/h
- 13.5 = specific volume of moist air at 70°F and 50% rh, ft^3/lb
- 1076 = average heat removal required to condense 1 lb of water vapor from room air, Btu/lb
- 7000 = grains per pound

The 6732 Btu/h of space latent load is equivalent to the latent load of 30 occupants (seated, very light work, 155 Btu/h per occupant) and the additional space latent load (e.g., infiltration latent load).

$$\text{Occupant latent load} = 30 \text{ Occupants} \times 155 \text{ Btu/h per occupant}$$
$$= 4650 \text{ Btu/h}$$

$$\text{Remainder of total dehumidification capability} = 6732 - 4650 = 2082 \text{ Btu/h}$$

This additional dehumidification capability can help in handling infiltration latent load and others.

This simple example demonstrates the ability of pre-dehumidified outdoor air to handle the space latent load, resulting in almost full separation of the space latent cooling load treatment from the space sensible cooling load. This approach allows only thermostatic control without losing humidity control in conditioned classrooms.

Typical DOAS are air-handling units that cool, dehumidify, heat, humidify and filter the outdoor air prior to being introduced to the conditioned space. Typical DOAS include the following major components:

- Mechanical cooling/dehumidification
  - DX coil
  - Chilled-water coil
- Desiccant-based cooling/dehumidification
  - Desiccant (dehumidification) and direct-expansion (DX) coil (post sensible cooling)
  - Desiccant (dehumidification) and chilled-water coil (post sensible cooling)

- Heating
  - Coils (hot-water, steam, electric, heat pump)
  - Gas-fired furnace
- Humidification
  - Passive (in conjunction with enthalpy wheel heat recovery)
  - Active (steam, electric-to-steam, gas-to-steam)
- Exhaust air recovery: air-to-air heat recovery
  - Rotary (enthalpy wheel, sensible wheel)
  - Fixed (heat pipe, plate heat exchanger, run around coils)
- Dehumidification enhancements for air-to-air heat recovery
  - Heat pipe based (wraparound coil)
  - Mini plate heat exchanger based

Which DOAS configuration is most cost-effective depends on variables such as availability of utilities (chilled water, gas, steam), space constraints, climatic data, utility cost, and budget. DOAS can be configured easily by using modular components that meet the design criteria. Selection and analysis software of these systems is readily available from DOAS manufacturers, which simplifies configuration and analysis of the most cost-effective system. Typical configurations of DOAS are shown in Figures 2 and 3. A cooling/dehumidification psychrometrics process of DOAS shown in Figure 4.

Given the need for more stringent and complex control schemes for outdoor air preconditioning, DOAS typically incorporate, direct digital control (DDC) systems, either stand-alone microprocessor-based or with the ability to communicate with central energy management system. The control system can be purchased as an option or installed in the field by the controls vendor. Typical supply air conditions for a DOAS air-handling unit are shown in Table 10.

Typical arrangements of DOAS integrated with local cooling and heating systems are shown in Figure 5.

Displacement Ventilation. Recently, use of displacement ventilation (as opposed to the more traditional mixing ventilation) for classrooms has been extended for enhanced IAQ and thermal comfort. In displacement ventilation, fresh air at colder temperature than the room air is discharged close to the floor level, and warm air is exhausted at or close to the ceiling. After being discharged at a low level, the colder supply air rises as it is heated by heat sources (e.g., people, computers), also allowing effective removal of containments generated in the room. Figure 6 shows a typical displacement ventilation arrangement for cooling.

Guidelines and procedures for designing displacement ventilation systems can be found in Chen and Glicksman (2003) and Skistad et al. (2002).

Typical displacement ventilation systems for classrooms include the following main subsystems (Figure 7):

- DOAS air-handling unit that can cool and dehumidify outdoor air to 60 to 62°F and 40 to 50 gr/lb for summer, and heat air to 65 to 68°F for winter
- Zone fan-powered terminal with sensible cooling capability (located outside the conditioned zone)
- Special displacement ventilation diffusers
- Heating radiators or convectors placed below windows in perimeter zones
- Control systems (thermostats and occupancy sensors)

In addition to the traditional displacement ventilation system described previously, displacement ventilation with induction can also be considered for classrooms. A displacement ventilation system with induction uses special terminals to provide additional cooling and heating with the displacement ventilation effect. These terminals are not equipped with fans, resulting in lower noise levels as required by more stringent noise criteria.

A displacement ventilation system with induction includes the following main subsystems:

- DOAS air-handling unit that can cool and dehumidify outdoor air to 54 to 57°F and 40 to 50 gr/lb for summer, and heat air to 65 to 68°F for winter

Table 10 Typical Design Criteria for DOAS Air-Handling Unit

	Supply Air Conditions[a]		Minimum Air Filtration Efficiency, MERV[b]
	Temperature, °F	Humidity Ratio, gr/lb	
Winter	65 to 68	30 to 40	6 to 8
Summer	60 to 65	40 to 60	6 to 8

Notes:
[a]Building location may dictate optimum supply condition in recommended range.
[b]Filter efficiency definition per ASHRAE *Standard* 52.2-1999.
MERV = minimum efficiency reporting values

Fig. 2 Typical Configuration of DOAS Air-Handling Unit: Enthalpy Wheel with Heat Pipe for Reheat
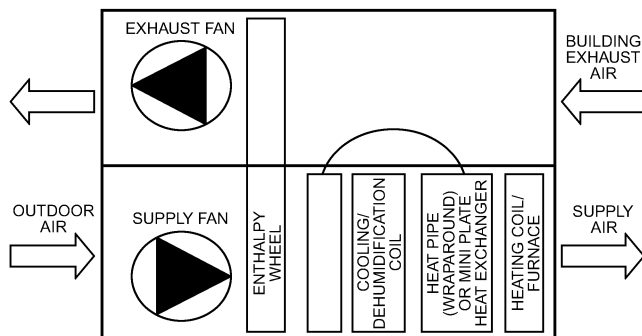
Fig. 3 Typical Configuration of DOAS Air-Handling Unit: Enthalpy Wheel with Wraparound Heat Pipe for Reheat
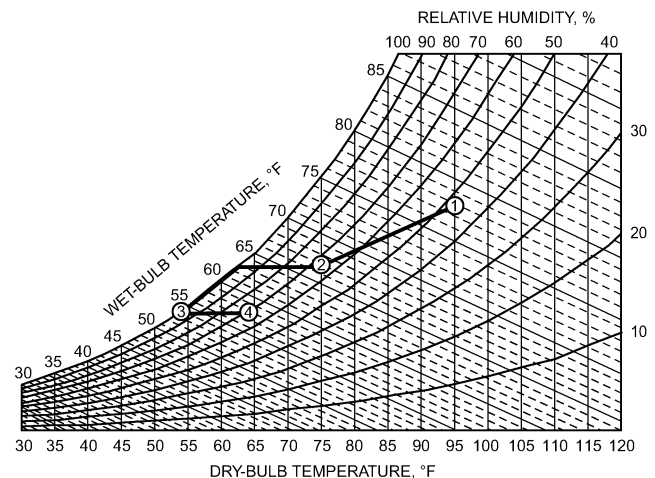
Fig. 4 Cooling/Dehumidification Psychrometric Process of Typical DOAS Air-Handling Unit in Figure 3
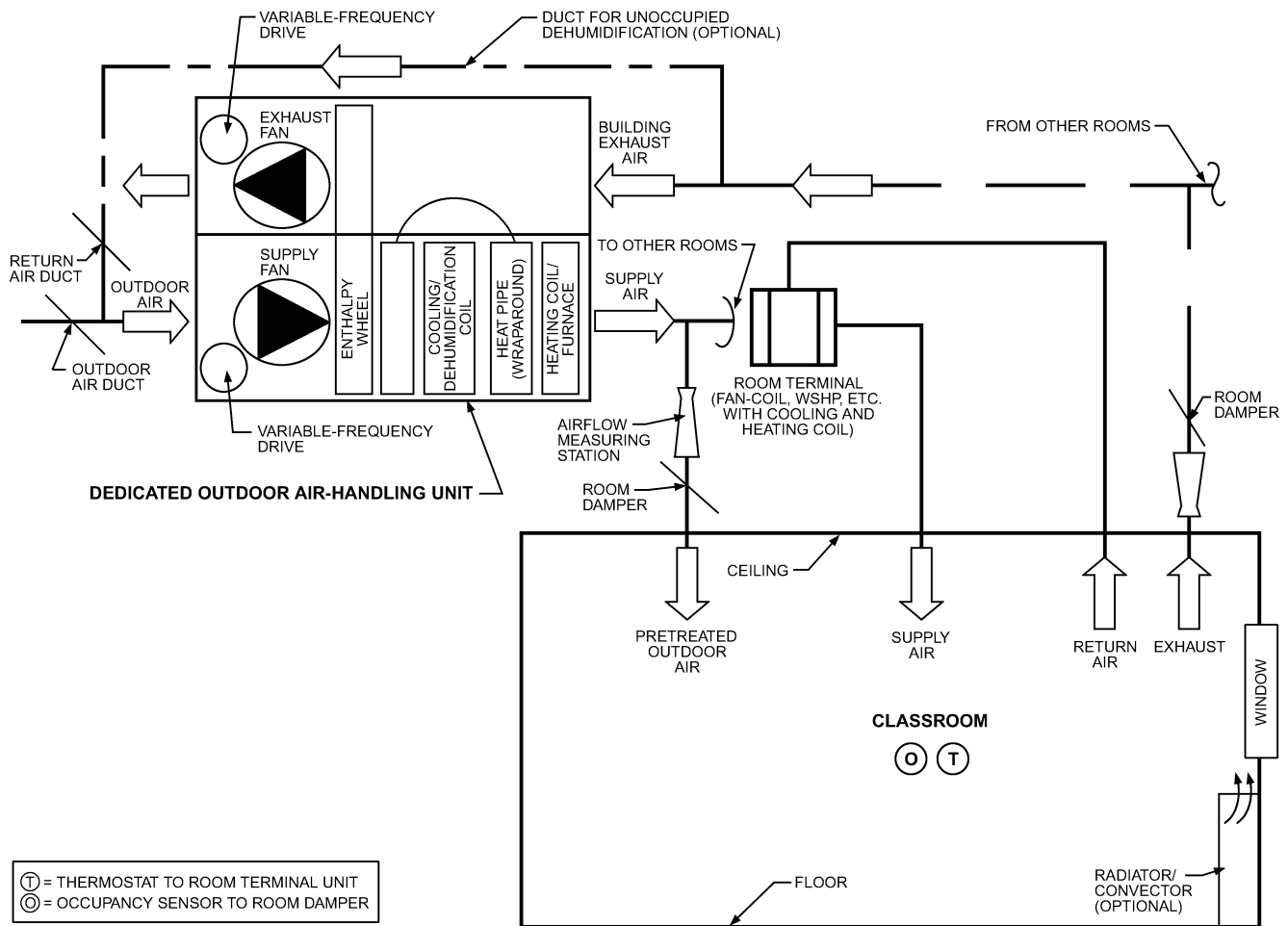
Fig. 5   Typical Schematic of DOAS with Local Classroom Cooling/Heating Terminal

- Zone displacement ventilation with induction terminal, equipped with two- or four-pipe cooling and heating coil mounted along perimeter walls and windows
- Control systems (thermostats and occupancy sensors)

   Systems Selection by Application. Table 11 shows the applicability of systems to areas in K-12 school facilities.

   Specialized Equipment. Areas such as natatoriums and ice rinks need specialized equipment to address the unique design requirements and the cooling, dehumidification, and heating characteristics of these areas. Natatoriums typically use special units that can introduce large quantities of outdoor air and allow active humidity control (mainly dehumidification). This equipment is similar to DOAS, and typically uses chilled water or a DX system for dehumidification. For systems with air-cooled condensers, condenser heat can be recovered to heat the swimming pool. See Chapter 4 of this volume for more information on natatoriums.

   Similarly, an ice rink requires special equipment; selection depends heavily on the school's location and seasonal use. Ice rink HVAC and dehumidification equipment can be desiccant-based or self-contained mechanical refrigeration. See Chapter 4 of this volume and Chapter 35 of the 2006 *ASHRAE Handbook—Refrigeration* for more information on ice rinks.

   Chapters 27 and 28 of Harriman et al. (2001) also provide detailed information on humidity control for natatoriums and ice rinks, respectively.

Energy Considerations

   Energy design guidelines and standards are well covered by ANSI/ASHRAE *Standard* 90.1-2004 and its user's manual (ASHRAE 2004b) and local energy codes. The designer should consult these standards for minimum energy criteria for schools, and consider the following energy conservation measures:

- **EMS/DDC systems** allow easier maintenance of comfort conditions, optimized operation, troubleshooting, and monitoring
- **Setback** (winter) or **setup** (summer) by central EMS or stand-alone programmable thermostats
- **Morning warm-up** (winter) and **cooldown** (summer), typically by the central EMS or stand-alone microprocessor-based control systems
- **Zone ventilation control** with zone occupancy sensors by throttling the space outdoor air damper to minimum position or closed during unoccupied hours
- **Enhanced summer humidity control** by switching the DOAS unit from 100% outdoor air to 100% recirculation and maintaining the required summer humidity dew-point temperature
- **Evaporative cooling systems**, where and when applicable
- **Geothermal systems**, when applicable
- **Ceiling fans**, typically for gymnasiums
- **Natural ventilation**, when applicable, by operable windows
- **Passive heating and cooling**, incorporated in cooperation with the architect
- **Solar heating**, when economically justifiable for domestic hot-water heating and space heating

- **Hot- and chilled-water temperature reset**, for systems with central plants (chillers and boilers); note, however, that chilled-water temperature reset might compromise the dehumidification capability of the system, and should be applied only if ambient humidity permits

    Demand Control Ventilation (DCV). Demand control ventilation can reduce the cost of operating the HVAC systems. To ensure proper IAQ and comply with ANSI/ASHRAE *Standard* 62.1-2004 and local codes that permit DCV, the designer must carefully follow
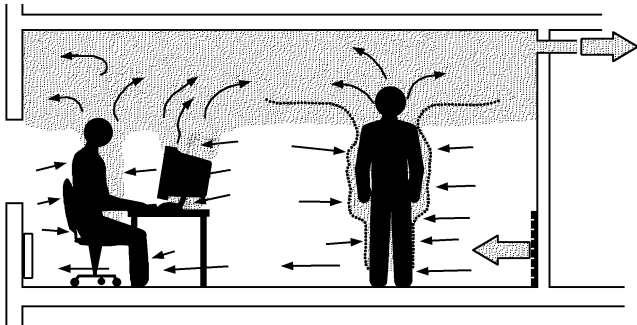
Fig. 6   Displacement Ventilation
(Skistad et al. 2002)

section 6.2.7 (Dynamic Reset) of *Standard* 62.1 and corresponding sections of the user's manual (ASHRAE 2004a). *Standard* 62.1-2004 explicitly allows use of CO_2 levels or occupancy to reset intake airflow in response to space occupancy levels. Special attention should be given to the area served by the HVAC system and the system type. Areas such as gymnasiums and auditoriums can benefit from CO_2-based DCV, commonly used in single-zone systems without DOAS, serving one space with varying occupancy. In these cases, DCV control is simple, reliable, and cost-effective. Systems such as multizone VAV with recirculated air without DOAS require special attention to ensure adequate OA supply to multiple zones under varying loads (such as classrooms). This problem complicates the design, operation, and maintenance of DCV control systems and also adds the cost of additional sensors.

    A simpler approach for DCV is in systems that use DOAS: the OA supply to each individual space can be controlled independently by occupancy sensors that can reduce the OA to a preset value (and also turn off the lights), or by CO_2 sensors (see Figure 5).

COLLEGES AND UNIVERSITIES

General and Design Considerations

    College and university facilities are similar to those of middle and high schools, except that there are more of them, usually housed in several buildings on the campus. Some colleges and universities have satellite campuses scattered throughout a city or a state. The design
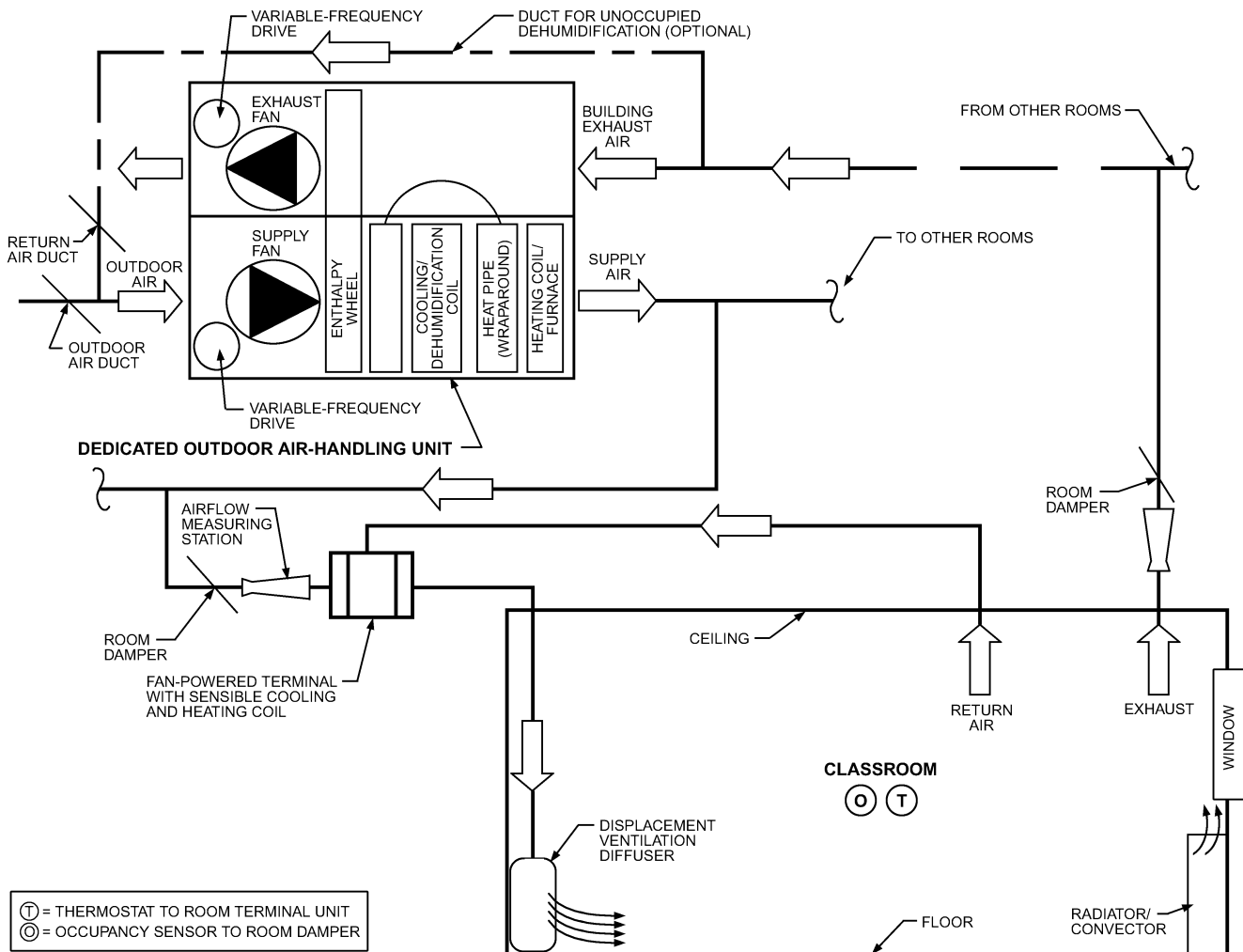
Fig. 7   Typical Displacement Ventilation System Layout

Table 11   Applicability of Systems to Typical Areas

Typical Area[c]	Centralized			Decentralized				Heating Only	
	SZ[a]	VAV/ Reheat	Fan Coil (Two- and Four-Pipe)	PSZ/ SZ[a] Split	PVAV/ Reheat	WSHP	Geothermal Heat Pump	Baseboard/ Radiators	Unit Heaters
Classrooms	X	X	X	X	X	X	X	X	
Laboratories and Science Facilities[b]	X	X	X	X	X	X	X	X	
Administrative Areas	X	X	X	X	X	X	X	X	
Gymnasium[e]	X	X		X					X
Libraries	X	X	X	X	X	X	X	X	
Auditorium[e]	X	X		X	X				
Home Economics Room	X	X	X	X	X	X	X	X	
Cafeteria[e]	X			X					
Kitchen[e]	X			X					X
Auto Repair Shop									X
Industrial Shop									X
Locker Rooms								X	X
Ventilation (Outdoor Air)	DOAS	[d]	DOAS	DOAS	[d]	DOAS	DOAS	DOAS	DOAS

SZ = single zone
PVAV = packaged variable-air-volume

VAV = variable-air-volume
WSHP = water-source heat pump

PSZ = packaged single zone
DOAS = dedicated outdoor air system

Notes:
[a]SZ and PSZ/SZ split for classrooms requires individual thermostatic control.
[b]Systems for laboratories must comply with local codes and be in accordance with current practices for laboratories.
[c]Systems and equipment for ice rinks and natatoriums not shown; refer to specialized equipment section.

[d]Special attention should be given for adequate OA supply in VAV applications without DOAS; consult ANSI/ASHRAE *Standard* 62.1-2004 Section 6.2.5, and corresponding section in user's manual (ASHRAE 2004a).
[e]In some cases, these areas can be served by SZ, WSHP, and geothermal HP systems without OA from DOAS.

criterion for each building is established by the requirements of its users. The following are major facilities commonly found on college and university campuses, but not usually in middle and high schools:

Administrative Buildings. These buildings should be treated as office buildings. They usually have a constant interior load and additional part-time loads associated with spaces such as conference rooms.

Vivariums (Animal Facilities). These spaces are commonly associated with laboratories, but usually have their own separate areas. Animal facilities need close temperature control and require a significant amount of outdoor ventilation to control odors and prevent the spread of diseases among the animals. Animal facilities are discussed in Chapters 14 and 22 of this volume, and in Chapter 10 of the 2005 *ASHRAE Handbook—Fundamentals*.

Dormitory Buildings. See Chapter 5.

Storage Buildings. These buildings are usually heated and ventilated only; however, part of the facility may require temperature and humidity control, depending upon the materials stored there.

Student and Faculty Apartment Buildings. See Chapter 5.

Large Gymnasiums. See Chapter 4.

Laboratory Buildings. These buildings house research facilities and may contain fume hoods, machinery, lasers, vivariums, areas with controlled environments, and departmental offices. The HVAC systems and control must be able to accommodate diverse functions of the facility, which may have 24 h, year-round operation, and yet be easy to service and quick to repair. Variable-air-volume (VAV) systems can be used in laboratory buildings. Proper control systems should be applied to introduce and extract the required quantities of supply and exhaust air. Maintaining the required space pressure differential to adjacent spaces and the minimum airflow under all circumstances is extremely critical for laboratory safe operation. Energy can be saved by recovering energy from exhaust air and tempering outdoor makeup air. Special attention should be given to containments in the exhaust airstream. Potential carryover of air from exhaust air to supply air, and interaction with the energy recovery device adsorbent for cases with total (sensible and latent) energy recovery, should be examined. In general, air exhausted from fume hoods should not be used for energy recovery. Other energy-saving systems used for laboratory buildings include (1) ice storage, (2) heat reclaim chillers to produce domestic hot water or hot water for booster coils in the summer, and (3) cooling-tower free cooling.

The design engineer should discuss expected contaminants and concentrations with the owner to determine construction materials for fume hoods and fume exhaust systems. Close coordination with health and safety (H&S) personnel is vital for safe laboratory building operation. Back-up or standby systems for emergency use should be considered, such as alarms on critical systems. Maintenance staff should be thoroughly trained in upkeep and repair of all systems, components, and controls. For additional information on laboratories and vivariums, see Chapter 14, ANSI/AIHA *Standard* Z9.5-2003, and McIntosh et al. (2001).

Museums. See Chapter 21.

Central Plants. These facilities contain generating equipment and other supporting machinery for buildings or campus heating and air conditioning. Central plants can serve a single building, cluster of buildings, or the entire campus (district heating and cooling plant). District heating and cooling plants are covered in Chapter 11 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*. Central plants are not conditioned and are generally heated and ventilated only.

Television and Radio Studios. See Chapter 3.

Hospital. Hospitals are discussed in Chapter 7 and ASHRAE's (2003) *HVAC Design Manual for Hospitals and Clinics*.

Chapels. See Chapter 4.

Student Unions. These facilities usually contain dining rooms, kitchens, meeting rooms, lounges, and game rooms. Student unions are generally open every day from early in the morning to late at night. An HVAC system such as VAV cooling with perimeter heating may be suitable. Extra ventilation air is required as makeup air for kitchen systems and for the building's potential high occupancy. See Chapters 3 and 31 for additional information.

Lecture Halls. These spaces house large numbers of students for a few hours several times a day and are vacant the rest of the time,

so heat loads vary throughout the day. Systems serving lecture halls must respond to these load variations. In addition, because the rooms are often configured such that students at the rear of the room are seated nearer the ceiling, the systems must run quietly and must not produce drafts. Coordination with the design team is essential for determining the optimal location of diffusers and return grilles and registers. Placement of supply diffusers at the front of the room and return air grilles and registers near the front and rear of the room or under seats should be considered. An analysis of the system noise levels expected in the hall is recommended. See Chapter 47 for further information.

Energy Considerations

All the energy considerations discussed in the section on K-12 Schools can be applied successfully in colleges and universities.

Central Plants. Large central plants can serve a single building, cluster of buildings, or the entire site. District central plants can generate chilled water and/or steam for distribution to the buildings it serves. In many cases, each building is equipped with secondary chilled-water pumps and steam-to-water heat exchangers. See Chapter 11 of the 2004 *ASHRAE Handbook—HVAC System and Equipment* for additional information on district cooling and heating. Chilled-water and steam flow-measuring stations should be used to monitor each building's energy use.

Energy conservation measures applicable to large central plants include the following:

- Chiller plant optimization control system
- Winter free cooling
- Chilled water and ice storage
- Microprocessor-based air/fuel control in conjunction with steam pressure control and optimal boiler sequencing control
- Dual-fuel boilers
- Blowdown heat recovery
- Boiler stack economizer
- Energy monitoring

More information can be found in Wulfinghoff (2000).

Where economically justifiable, chilled water and steam can be purchased from an independent operator.

Combined heat and power (CHP) plants can be considered for large facilities when economically justifiable. Chapter 7 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment* and Orlando (1996) provide information on CHP systems.

SEISMIC AND WIND RESTRAINT CONSIDERATIONS

Seismic bracing of HVAC equipment should be considered. Wind restraint codes may also apply in areas where tornados and hurricanes necessitate additional bracing. This consideration is especially important if there is an agreement with local officials to use the facility as a disaster relief shelter. See Chapter 54 for further information.

COMMISSIONING

Commissioning is a quality assurance process for buildings from predesign through design, construction, and operations. The commissioning process involves achieving, verifying, and documenting the performance of each system to meet the building operational needs. Given the criticality of issues such as indoor air quality, thermal comfort, noise, etc., in educational facilities and the application of equipment and systems such as DOAS, EMS, and occupancy sensors, it is important to follow the commissioning process as described in Chapter 42 and ASHRAE *Guideline* 0-2005. Proper commissioning ensures fully functional systems that can be operated and maintained properly throughout the life of the building.

SUSTAINABLE DESIGN

A trend in the educational community to embrace the principles of sustainable design has increased in the last several years. Begun as a means to educate the students in conserving earth resources, this approach also provides benefits such as enhanced IAQ and lower operating costs. Many schools are seeking Leadership in Energy and Environmental Design (LEED) certification as administrated by the U.S. Green Building Council (USGBC). The LEED system awards credits in six categories:

- Sustainable sites
- Water efficiency
- Energy and atmosphere
- Materials and resources
- Indoor environmental quality
- Innovation and design process

The HVAC&R designer plays a major role in supporting the design team in demonstrating fulfillment of the prerequisites and supporting the analysis for credits.

Typically, the HVAC&R designer is heavily involved in the (1) energy and atmosphere and (2) indoor environmental quality categories. In the energy and atmosphere category, the HVAC&R designer, along with the architect, electrical engineers, and plumbing engineers, demonstrate compliance with ASHRAE *Standard* 90.1-2004 (as a prerequisite). They then typically perform whole-building energy simulation (using ASHRAE *Standard* 90.1-2004, Appendix G procedures) to demonstrate energy cost savings. The number of credits awarded is in correlation to the energy cost reduction. The HVAC&R designer is also involved in specifying HVAC&R equipment with environmentally friendly refrigerants, improved ventilation techniques (e.g., displacement ventilation), water conservation, etc. Additional information on LEED certification can be found in Grumman (2003) and USGBC (2005).

For laboratories, the designer can use information from the U.S. Environmental Protection Agency's (EPA 2000) sustainable design initiative, *Laboratories for the 21st Century (Labs21)*.

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CHAPTER 7

HEALTH CARE FACILITIES

CONTINUAL advances in medicine and technology necessitate constant reevaluation of the air-conditioning needs of hospitals and medical facilities. Medical evidence has shown that proper air conditioning is helpful in preventing and treating many conditions, but the relatively high cost of air conditioning demands efficient design and operation to ensure economical energy management (Demling and Maly 1989; Fitzgerald 1989; Murray et al. 1988; Woods et al. 1986).

Health care occupancy classification, based on the latest occupancy guidelines from the National Fire Protection Association (NFPA) Life Safety Code®, should be considered early in project design. Health care occupancy is important for fire protection (smoke zones, smoke control) and for future adaptability of the HVAC system for a more restrictive occupancy.

Health care facilities are increasingly diversifying in response to a trend toward outpatient services. The term **clinic** may refer to any building from the ubiquitous residential doctor's office to a specialized cancer treatment center. Prepaid health maintenance provided by integrated regional health care organizations is becoming the model for medical care delivery. These organizations, as well as long-established hospitals, are constructing buildings that look less like hospitals and more like luxury hotels and office buildings.

For the purpose of this chapter, health care facilities are divided into the following categories:

• Hospital facilities
• Outpatient health care facilities
• Nursing facilities
• Dental care facilities

The specific environmental conditions required by a particular medical facility may vary from those in this chapter, depending on the agency responsible for the environmental standard. Among the agencies that may have standards and guidelines for medical facilities are state and local health agencies, the U.S. Department of Health and Human Services, Indian Health Service, Public Health Service, Medicare/Medicaid, U.S. Department of Defense, U.S. Department of Veterans Affairs, and Joint Commission on Accreditation of Healthcare Organizations (JCAHO). The American Institute of Architects (AIA 2006) requires the owner to provide an Infection Control Risk Assessment (ICRA) and prepare Infection Control Risk Mitigation Recommendations (ICRMR). The ICRMR and ICRA are then to be incorporated in the contract documents by the design professional. Therefore, it is advisable to discuss infection control objectives with the hospital's infection control committee.

The general hospital was selected as the basis for the fundamentals outlined in the first section, Hospital Facilities, because of the variety of services it provides. Environmental conditions and design criteria apply to comparable areas in other health facilities.

The general acute care hospital has a core of critical-care spaces, including operating rooms, emergency rooms, delivery rooms, and a nursery. Usually the functions of radiology, laboratory, central sterile, and pharmacy are located close to the critical care space. Inpatient nursing, including intensive care nursing, is in the complex. The facility also incorporates a kitchen, dining and food service, morgue, and central housekeeping support.

Criteria for outpatient facilities are given in the second section. Outpatient surgery is performed with the anticipation that the patient will not stay overnight. An outpatient facility may be part of an acute care facility, a freestanding unit, or part of another medical facility such as a medical office building.

Nursing facilities are addressed separately in the third section, because their fundamental requirements differ greatly from those of other medical facilities.

Dental facilities are briefly discussed in the fourth section. Requirements for these facilities differ from those of other health care facilities because many procedures generate aerosols, dusts, and particulates.

AIR CONDITIONING IN DISEASE PREVENTION AND TREATMENT

Hospital air conditioning plays a more important role than just the promotion of comfort. In many cases, proper air conditioning is a factor in patient therapy; in some instances, it is the major treatment.

Studies show that patients in controlled environments generally have more rapid physical improvement than do those in uncontrolled environments. Patients with thyrotoxicosis do not tolerate hot, humid conditions or heat waves very well. A cool, dry environment favors the loss of heat by radiation and evaporation from the skin and may save the patient's life.

Cardiac patients may be unable to maintain the circulation necessary to ensure normal heat loss. Therefore, air conditioning cardiac wards and rooms of cardiac patients, particularly those with congestive heart failure, is necessary and considered therapeutic (Burch and Pasquale 1962). Individuals with head injuries, those subjected to brain operations, and those with barbiturate poisoning may have hyperthermia, especially in a hot environment, due to a disturbance in the heat regulatory center of the brain. An important factor in recovery is an environment in which the patient can lose heat by radiation and evaporation: namely, a cool room with dehumidified air.

A hot, dry environment of 90°F db and 35% rh has been successfully used in treating patients with rheumatoid arthritis.

Dry conditions may be hazardous to the ill and debilitated by contributing to secondary infection or infection totally unrelated to the clinical condition causing hospitalization. Clinical areas devoted to upper respiratory disease treatment and acute care, as well as the general clinical areas of the entire hospital, should be maintained at 30 to 60% rh.

Patients with chronic pulmonary disease often have viscous respiratory tract secretions. As these secretions accumulate and increase in viscosity, the patient's exchange of heat and water dwin-

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The preparation of this chapter is assigned to TC 9.6, Health Care Facilities.

dles. Under these circumstances, the inspiration of warm, humidified air is essential to prevent dehydration (Walker and Wells 1961).

Patients needing oxygen therapy and those with tracheotomies require special attention to ensure warm, humid supplies of inspired air. Cold, dry oxygen or bypassing the nasopharyngeal mucosa presents an extreme situation. Rebreathing techniques for anesthesia and enclosure in an incubator are special means of addressing impaired heat loss in therapeutic environments.

Burn patients need a hot environment and high relative humidity. A ward for severe burn victims should have temperature controls that permit adjusting the room temperature up to 90°F db and relative humidity up to 95%.

HOSPITAL FACILITIES

Although proper air conditioning is helpful in preventing and treating disease, application of air conditioning to health facilities presents many problems not encountered in usual comfort conditioning design.

The basic differences between air conditioning for hospitals (and related health facilities) and that for other building types stem from the (1) need to restrict air movement in and between the various departments; (2) specific requirements for ventilation and filtration to dilute and remove contamination (odor, airborne microorganisms and viruses, and hazardous chemical and radioactive substances); (3) different temperature and humidity requirements for various areas; and (4) design sophistication needed to permit accurate control of environmental conditions.

Infection Sources and Control Measures

Bacterial Infection. Examples of bacteria that are highly infectious and transported within air or air and water mixtures are *Mycobacterium tuberculosis* and *Legionella pneumophila* (Legionnaires' disease). Wells (1934) showed that droplets or infectious agents of 5 μm or less in size can remain airborne indefinitely. Isoard et al. (1980) and Luciano (1984) have shown that 99.9% of all bacteria present in a hospital are removed by 90 to 95% efficient filters (ASHRAE *Standard* 52.1), because bacteria are typically present in colony-forming units that are larger than 1 μm. Some authorities recommend the use of high-efficiency particulate air (HEPA) filters having dioctyl phthalate (DOP) test filtering efficiencies of 99.97% in certain areas.

Viral Infection. Examples of viruses that are transported by and virulent within air are *Varicella* (chicken pox/shingles), *Rubella* (German measles), and *Rubeola* (regular measles). Epidemiological evidence and other studies indicate that many of the airborne viruses that transmit infection are submicron in size; thus, there is no known method to effectively eliminate 100% of the viable particles. HEPA and/or ultralow-penetration (ULPA) filters provide the greatest efficiency currently available. Attempts to deactivate viruses with ultraviolet light and chemical sprays have not proven reliable or effective enough to be recommended by most codes as a primary infection control measure. Therefore, isolation rooms and isolation anterooms with appropriate ventilation-pressure relationships are the primary means used to prevent the spread of airborne viruses in the health care environment.

Molds. Evidence indicates that some molds such as *Aspergillis* can be fatal to advanced leukemia, bone marrow transplant, and other immunocompromised patients.

Outside Air Ventilation. If outside air intakes are properly located, and areas adjacent to the intakes are properly maintained, outside air, in comparison to room air, is virtually free of bacteria and viruses. Infection control problems frequently involve a bacterial or viral source within the hospital. Ventilation air dilutes viral and bacterial contamination within a hospital. If ventilation systems are properly designed, constructed, and maintained to preserve correct pressure relations between functional areas, they remove airborne infectious agents from the hospital environment.

Temperature and Humidity. These conditions can inhibit or promote the growth of bacteria and activate or deactivate viruses. Some bacteria such as *Legionella pneumophila* are basically waterborne and survive more readily in a humid environment. Codes and guidelines specify temperature and humidity range criteria in some hospital areas as a measure for infection control as well as comfort.

AIR QUALITY

Systems must also provide air virtually free of dust, dirt, odor, and chemical and radioactive pollutants. In some cases, outside air is hazardous to patients suffering from cardiopulmonary, respiratory, or pulmonary conditions. In such instances, systems that intermittently provide maximum allowable recirculated air should be considered.

Outside Air Intakes. These intakes should be located as far as practical (on directionally different exposures whenever possible), but not less than 25 ft, from combustion equipment stack exhaust outlets, ventilation exhaust outlets from the hospital or adjoining buildings, medical-surgical vacuum systems, cooling towers, plumbing vent stacks, smoke control exhaust outlets, and areas that may collect vehicular exhaust and other noxious fumes. The bottom of outside air intakes serving central systems should be located as high as practical (12 ft recommended) but not less than 6 ft above ground level or, if installed above the roof, 3 ft above the roof level.

Exhaust Outlets. These exhausts should be located a minimum of 10 ft above ground level and away from doors, occupied areas, and operable windows. Preferred location for exhaust outlets is at roof level projecting upward or horizontally away from outside intakes. Care must be taken in locating highly contaminated exhausts (e.g., from engines, fume hoods, biological safety cabinets, kitchen hoods, and paint booths). Prevailing winds, adjacent buildings, and discharge velocities must be taken into account (see Chapter 16 of the 2005 *ASHRAE Handbook—Fundamentals*). In critical or complicated applications, wind tunnel studies or computer modeling may be appropriate.

Air Filters. A number of methods are available for determining the efficiency of filters in removing particulates from an airstream (see Chapter 24 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*). All central ventilation or air-conditioning systems should be equipped with filters having efficiencies no lower than those indicated in Table 1. Where two filter beds are indicated, Filter Bed No. 1 should be located upstream of air-conditioning equipment, and Filter Bed No. 2 should be downstream of the supply fan. Appropriate precautions should be observed to prevent wetting the filter media by free moisture from humidifiers. Where only one filter bed is indicated, it should be located upstream of air-conditioning equipment. All filter efficiencies are based on ASHRAE *Standard* 52.2.

The following are guidelines for filter installations:

• HEPA filters with Minimum Efficiency Reporting Values (MERV) of 17 should be used on air supplies serving protective-environment rooms for clinical treatment of patients with a high susceptibility to infection due to leukemia, burns, bone marrow transplant, organ transplant, or human immunodeficiency virus (HIV). HEPA filters should also be used on discharge air from fume hoods or safety cabinets in which infectious or highly toxic or radioactive materials are processed. The filter system should be designed and equipped to permit safe removal, disposal, and replacement of contaminated filters.

• Filters should be installed to prevent leakage between filter segments and between the filter bed and its supporting frame. A small leak that permits any contaminated air to escape through the filter can destroy the usefulness of the best air cleaner.

Table 1 Filter Efficiencies for Central Ventilation and Air-Conditioning Systems in General Hospitals

Minimum Number of Filter Beds	Area Designation	Filter Efficiencies, MERV[a] Filter Bed No. 1	Filter Efficiencies, MERV[a] Filter Bed No. 2
2	Orthopedic operating room Bone marrow transplant operating room Organ transplant operating room	8	17[b]
2	General procedure operating rooms Delivery rooms Nurseries Intensive care units Patient care rooms Treatment rooms Diagnostic and related areas	8	14
1	Laboratories Sterile storage	13	
1	Food preparation areas Laundries Administrative areas Bulk storage Soiled holding areas	8	

[a]MERV = Minimum Efficiency Reporting Value based on ASHRAE *Standard* 52.2-1999.
[b]HEPA filters at air outlets.

- At minimum, a manometer should be installed in the filter system to measure pressure drop across each filter bank. Visual observation is not accurate for determining filter loading.
- High-efficiency filters should be installed in the system, with adequate facilities provided for maintenance and in situ filtration performance testing without introducing contamination into the delivery system or the area served.
- Because high-efficiency filters are expensive, the hospital should project the filter bed life and replacement costs and incorporate these into the operating budget. Control sequences to monitor and alarm, including ability to normalize or benchmark pressure drops and associated airflows, can enhance indication of filter loading when air handlers operate at less than design flow.
- During construction, openings in ductwork and diffusers should be sealed to prevent intrusion of dust, dirt, and hazardous materials. Such contamination is often permanent and provides a medium for growth of infectious agents. Existing or new filters as well as coils may rapidly become contaminated by construction dust.

Air Movement

The data given in Table 2 illustrate the degree to which contamination can be dispersed into the air of the hospital environment by one of the many routine activities for normal patient care. The bacterial counts in the hallway clearly indicate the spread of this contamination.

Because of the dispersal of bacteria resulting from such necessary activities, air-handling systems should provide air movement patterns that minimize the spread of contamination. Undesirable airflow between rooms and floors is often difficult to control because of open doors, movement of staff and patients, temperature differentials, and stack effect, which is accentuated by vertical openings such as chutes, elevator shafts, stairwells, and mechanical shafts common to hospitals. Although some of these factors are beyond practical control, the effect of others may be minimized by terminating shaft openings in enclosed rooms and by designing and balancing air systems to create positive or negative air pressure within certain rooms and areas.

Systems serving highly contaminated areas, such as autopsy and airborne infectious isolation rooms, must maintain a negative air

Table 2 Influence of Bedmaking on Airborne Bacterial Count in Hospitals

Item	Count per Cubic Foot Inside Patient Room	Count per Cubic Foot Hallway near Patient Room
Background	34	30
During bedmaking	140	64
10 min after	60	40
30 min after	36	27
Background	16	
Normal bedmaking	100	
Vigorous bedmaking	172	

Source: Greene et al. (1960).

pressure in these rooms relative to adjoining rooms or the corridor (Murray et al. 1988). The negative pressure difference is obtained by supplying less air to the area than is exhausted from it (CDC 1994). Protective-environment rooms exemplify positive or negative pressure conditions. Exceptions to normally established negative and positive pressure conditions include operating rooms where highly infectious patients may be treated (e.g., operating rooms in which bronchoscopy or lung surgery is performed) and infectious isolation rooms that house immunosuppressed patients with airborne infectious diseases such as tuberculosis (TB). These areas should include an anteroom between the operating or protective-environment room and the corridor or other contiguous space. The three common approaches to anteroom relative pressurization are (1) anteroom positive to both the room and contiguous space, (2) anteroom negative to both the room and contiguous space, and (3) anteroom positive to room, negative to contiguous space. Current thinking is that the anteroom should be always positive to corridor and surrounding space when used in a protective-environment setting. Any of these techniques minimizes cross-contamination between the patient area and surrounding areas, and may be used depending on local fire smoke management regulations.

Pressure differential causes air to flow in or out of a room through various leakage areas (e.g., perimeter of doors and windows, utility/fixture penetrations, cracks, etc.). A level of differential air pressure (0.01 in. of water) can be maintained only in a tightly sealed room. Therefore, it is important to obtain a reasonably close fit of all doors and seal all walls and floors, including penetrations between pressurized areas. Opening a door between two areas immediately reduces any existing pressure differential between them to such a degree that its effectiveness is nullified. When such openings occur, a natural interchange of air takes place between the two rooms because of turbulence created by the door opening and closing combined with personnel ingress/egress.

For critical areas requiring both the maintenance of pressure differentials to adjacent spaces and personnel movement between the critical area and adjacent spaces, the use of appropriate anterooms must be considered.

Figure 1 shows the bacterial count in a surgery room and its adjoining rooms during a normal surgical procedure. These bacterial counts were taken simultaneously. The relatively low bacterial counts in the surgery room, compared with those of the adjoining rooms, are attributable to the lower level of activity and higher air pressure in operating rooms.

In general, outlets supplying air to sensitive ultraclean areas should be located on the ceiling, and perimeter or several exhaust outlets should be near the floor. This arrangement provides downward movement of clean air through the breathing and working zones to the floor area for exhaust. There are two recognized approaches to infectious isolation room air distribution. One approach locates the supply air above and near the doorway, and exhaust air from near the floor behind the patient's bed. This arrangement has the intent of controlling the flow of clean air first to parts of the room
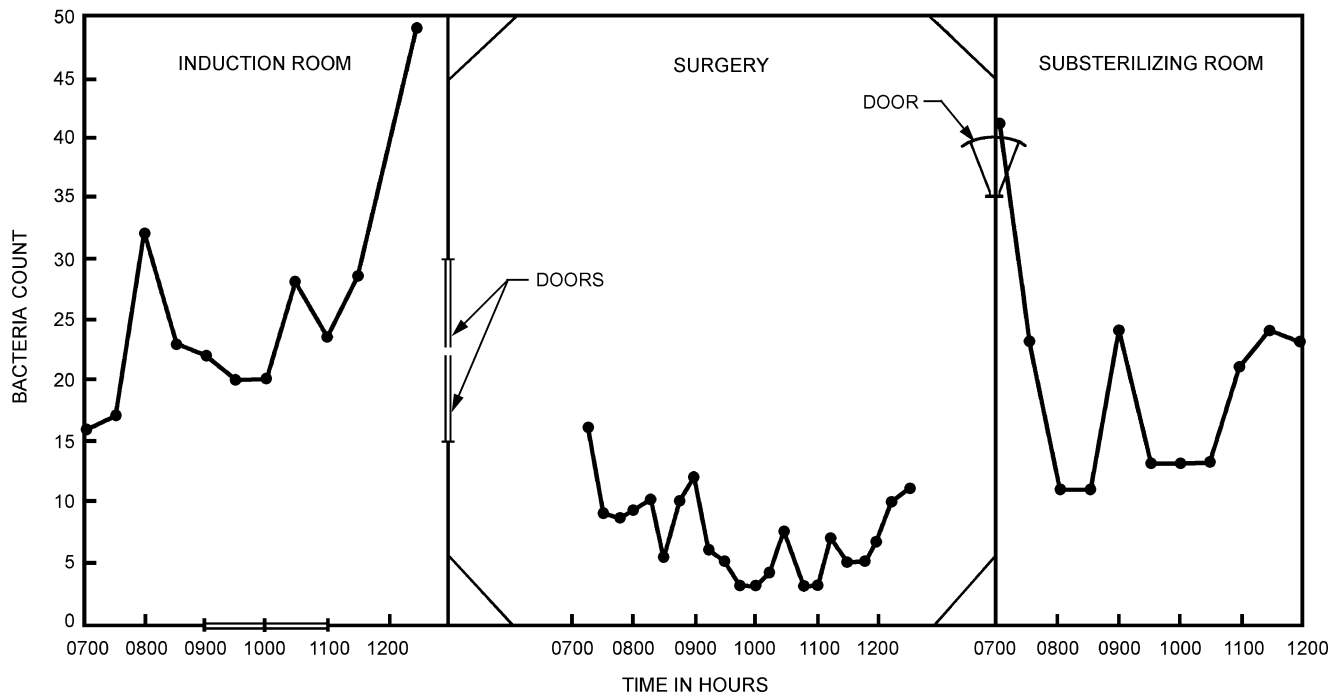
Fig. 1   Typical Airborne Contamination in Surgery and Adjacent Areas

where workers or visitors are likely to be, and across the infected source into the exhaust. The limited ability of this arrangement to achieve this directional airflow movement, in view of the relatively low air exchange rates involved and the minimal influence of the exhaust outlet, led others to advocate a second arrangement in which the supply diffuser and exhaust outlet are located to maximize room air mixing, and therefore contaminant removal, typically with ceiling-mounted supply and exhaust outlets over the patient bed or on the wall behind the bed. With this arrangement, the supply diffusers must be carefully selected and located such that primary air throw does not induce bedroom air to enter the anteroom.

The laminar airflow concept developed for industrial clean room use has attracted interest from some medical authorities. There are advocates of both vertical and horizontal laminar airflow systems, with and without fixed or movable walls around the surgical team (Pfost 1981). Some medical authorities do not advocate laminar airflow for surgeries but encourage air systems similar to those described in this chapter.

Laminar airflow in surgical operating rooms is predominantly unidirectional when not obstructed; this airflow pattern is commonly attained at a velocity of 90 ± 20 fpm. Laminar airflow has shown promise in rooms used for treating patients who are highly susceptible to infection (Michaelson et al. 1966).

Temperature and Humidity

Specific recommendations for design temperatures and humidities are given in the section on Specific Design Criteria. Temperature and humidity for other inpatient areas not covered should be 75°F or less and 30% to 60% rh.

Pressure Relationships and Ventilation

Table 3 covers ventilation recommendations for comfort, asepsis, and odor control in areas of acute care hospitals that directly affect patient care. If specific organizational criteria must be met, refer to that organization's literature. Ventilation in accordance with ASHRAE *Standard* 62.1, Ventilation for Acceptable Indoor Air Quality, should be used for areas where specific standards are

not given. Where a higher outside air requirement is called for in ASHRAE *Standard* 62.1 than in Table 3, the higher value should be used. Specialized patient care areas, including organ transplant and burn units, should have additional ventilation provisions for air quality control as may be appropriate.

Ventilation system design must as much as possible provide air movement from clean to less clean areas. In critical-care areas, constant-volume systems should be used to ensure proper pressure relationships and ventilation. In noncritical patient care areas and staff rooms, variable air volume (VAV) systems may be considered for energy conservation. When using VAV systems in the hospital, special care should be taken to ensure that minimum ventilation rates (as required by codes) are maintained and that pressure relationships between various spaces are maintained. With VAV systems, a method such as air volume tracking between supply, return, and exhaust could be used to control pressure relationships (Lewis 1988).

The number of air changes may be reduced to 25% of the indicated value when the room is unoccupied, if provisions are made to ensure that (1) the number of air changes indicated is reestablished whenever the space is occupied, and (2) the pressure relationship with the surrounding rooms is maintained when the air changes are reduced.

In areas requiring no continuous directional control (±), ventilation systems may be shut down when the space is unoccupied and ventilation is not otherwise needed.

Because of the cleaning difficulty and potential for buildup of contamination, recirculating room heating and/or cooling units must not be used in areas marked "No." Note that the standard recirculating room unit may also be impractical for primary control where exhaust to the outside is required.

In rooms with hoods, extra air must be supplied for hood exhaust so that the designated pressure relationship is maintained. Refer to Chapter 14, Laboratories, for further discussion of laboratory ventilation.

For maximum energy conservation, using recirculated air is preferred. If all-outside air is used, an efficient heat recovery method should be considered.

Smoke Control

As the ventilation design is developed, a proper smoke control strategy must be considered. Passive systems rely on fan shutdown and smoke and fire barriers. Proper treatment of duct penetrations must be observed.

Active smoke control systems use the ventilation system to create areas of positive and negative pressures that, along with fire and smoke partitions, limit the spread of smoke. The ventilation system may be used in a smoke removal mode in which combustion products are exhausted by mechanical means. As design of active smoke control systems evolves, the engineer and code authority should carefully plan system operation and configuration. Refer to Chapter 52 and NFPA *Standards* 90A, 92A, and 101.

SPECIFIC DESIGN CRITERIA

There are seven principal divisions of an acute care general hospital: (1) surgery and critical care, (2) nursing, (3) ancillary, (4) administration, (5) diagnostic and treatment, (6) sterilizing and supply, and (7) service. Environmental requirements of each department/space in these divisions differ according to their function and procedures carried out in them. This section describes the functions of these departments/spaces and covers details of design requirements. Close coordination with health care planners and medical equipment specialists in mechanical design and construction of health facilities is essential to achieve the desired conditions.

Surgery and Critical Care

No area of the hospital requires more careful control of the aseptic condition of the environment than the surgical suite. Systems serving operating rooms, including cystoscopic and fracture rooms, require careful design to minimize the concentration of airborne organisms.

The greatest amount of bacteria found in the operating room comes from the surgical team and is a result of their activities during surgery. During an operation, most members of the surgical team are near the operating table, creating the undesirable situation of concentrating contamination in this highly sensitive area. There are three distinct classifications for surgery care areas class A, B, and C (ACS 2000) that generally support invasive procedures as defined in (AIA 2006).

Operating Rooms. Past studies of operating-room air distribution devices and observation of installations in industrial clean rooms indicate that delivering air from the ceiling, with a downward movement to several exhaust/return openings located low on opposite walls, is probably the most effective air movement pattern for maintaining the contamination concentration at an acceptable level. Completely perforated ceilings, partially perforated ceilings, and ceiling-mounted diffusers have been applied successfully (Pfost 1981). A mixture of low and high exhaust opening locations may work better than either all low or all high locations, with supply air at face velocities of around 25 to 35 fpm from a unidirectional laminar-flow ceiling array.

Operating room suites are typically in use no more than 8 to 12 h per day (except trauma centers and emergency departments). For energy conservation, the air-conditioning system should allow a reduction in the air supplied to some or all of the operating rooms when possible. Positive space pressure must be maintained at reduced air volumes to ensure sterile conditions. The time required for an inactive room to become usable again must be considered. Consultation with the hospital surgical staff will determine the feasibility of this feature.

A separate air exhaust system or special vacuum system should be provided for the removal of anesthetic trace gases. Medical vacuum systems have been used to remove nonflammable anesthetic gases (NFPA *Standard* 99). One or more outlets may be located in each operating room to connect the anesthetic machine scavenger hose.

Although good results have been reported from air disinfection of operating rooms by irradiation, this method is seldom used. The reluctance to use irradiation may be attributed to the need for special designs for installation, protective measures for patients and personnel, constant monitoring of lamp efficiency, and maintenance.

The following conditions are recommended for operating, catheterization, cystoscopic, and fracture rooms:

- The temperature and relative humidity set points should be adjustable by surgical staff. Systems should be capable of maintaining the space temperature in the lower end of the range (62°F) for specialized procedures such as cardiac surgery. Table 3 lists tolerable temperature ranges; however, these are not intended to be dynamic control ranges. Special or supplemental cooling equipment should be considered if this lower temperature negatively affects energy use for surrounding areas.
- Air pressure should be kept positive with respect to any adjoining rooms by supplying excess air.
- A differential-pressure-indicating device should be installed to permit air pressure readings in the rooms. Thorough sealing of all wall, ceiling, and floor penetrations, and tight-fitting doors are essential to maintaining readable pressure.
- Humidity indicator and thermometers should be located for easy observation.
- Filter efficiencies should be in accordance with Table 1.
- The entire installation should conform to requirements of NFPA *Standard* 99, Health Care Facilities.
- Air should be supplied at the ceiling with exhaust/return from at least two locations near the floor, with consideration given to having at least two high exhaust/return openings opposite from the low outlets. Endoscopic, laparoscopic, or thoracoscopic surgery procedures aided by camera, and robotic or robot-assisted surgery procedures, require heat-producing equipment in the operating room. Exhaust/return openings located above this equipment can capture the more buoyant heated air and prevent it from being reentrained in the ceiling supply airstream. The bottom of low openings should be at least 3 in. above the floor. Supply diffusers should be unidirectional (laminar-flow). High-induction ceiling or sidewall diffusers should be avoided.
- Total air exchange rates should address lights and equipment (e.g., blanket and blood warmers, fiber-optic equipment, robotic consoles). Suites with a large amount of electronic equipment have been reported to require 30 to 35 air changes per hour using conventional air-conditioning systems with 18 to 20°F supply temperature differentials.
- Acoustical materials should not be used as duct linings unless terminal filters of at least MERV 14 efficiency are installed downstream of the linings. Internal insulation of terminal units may be encapsulated with approved materials. Duct-mounted sound traps should be of the packless type or have polyester film linings over acoustical fill.
- Any spray-applied insulation and fireproofing should be treated with fungi growth inhibitor.
- Sufficient lengths of watertight, drained stainless steel duct should be installed downstream of humidification equipment to ensure complete evaporation of water vapor before air is discharged into the room.

Control centers that monitor and allow adjustment of temperature, humidity, and air pressure may be located at the surgical supervisor's desk.

Obstetrical Areas. The pressure in the obstetrical department should be positive or equal to that in other areas.

Delivery Rooms. The delivery room design should conform to the requirements of operating rooms.

Table 3   Ventilation Requirements for Areas Affecting Patient Care in Hospitals and Outpatient Facilities

Function Space	Pressure Relationship to Adjacent Areas[a]	Minimum Air Changes of Outside Air per Hour[b]	Minimum Total Air Changes per Hour[c]	All Air Exhausted Directly to Outside[m]	Air Recirculated Within Room Units[d]	Relative Humidity,[n] %	Design Temperature,[o] °F
Surgery and Critical Care							
Operating room (class B and positive C surgical)	Positive	4	20	—	No	30 to 60	62 to 80
Operating/surgical cystoscopic rooms[e, p, q]	Positive	4	20	—	No	30 to 60	68 to 73[r]
Delivery room[p]	Positive	4	20	—	No	30 to 60	68 to 73
Recovery room[p]	—*	2	6	—	No	30 to 60	75 ± 2
Critical or intensive care (burn or intermediate)	Positive*	2	6	—	No	30 to 60	70 to 75
Newborn intensive care	Positive*	2	6	—	No	30 to 60	72 to 78
Treatment room[s]	—*	2	6	—	—	30 to 60	70 to 75
Nursery suite	Positive	5	12	—	No	30 to 60	75 to 80
Trauma room[f, s]	Positive	5	12	—	No	30 to 60	70 to 75
Trauma room (crisis or shock)	—	3	15	—	No	30 to 60	70 to 75
Anesthesia gas storage	Negative	—	8	Yes	—	—	—
GI endoscopy[ab]	—	2	6	—	No	30 to 60	68 to 73
Bronchoscopy[q]	Negative	2	12	Yes	No	30 to 60	68 to 73
Emergency waiting rooms	Negative	2	12	Yes	—	30 to 60	70 to 75
Triage areas	Negative	2	12	Yes	—	—	70 to 75
Radiology waiting rooms	Negative	2	12	Yes[t]	—	—	70 to 75
Procedure room (class A surgical)	Positive	3	15	—	No	30 to 60	70 to 75
Nursing							
Patient room	—*	2	6[v]	—	—	30 (W), 50 (S)	70 to 75
Toilet room[g]	Negative	Optional	10	Yes	No	—	—
Newborn nursery suite	—*	2	6	—	No	30 to 60	72 to 78
Protective environment room[i, q, w]	Positive	2	12	—	No	—	70 to 75
Airborne infection isolation room[h, q, x]	Negative	—	12	Yes[u]	No	30 to 60	70 to 75
Isolation alcove or anteroom[w, x]	Pos./Neg.	2	10	Yes	No	—	—
Labor/delivery/recovery/postpartum (LDRP)	—*	2	6[v]	—	—	30 (W), 50 (S)	70 to 75
Public corridor	Negative	2	2	—	—	—	—
Patient corridor	—*	2	4	—	—	—	—
Ancillary							
Radiology (diagnostic and treatment)	—	2	6	—	—	40 (W), 50 (S)	78 to 80
Radiology (surgery/critical care and catheterization)	Positive	3	15	—	No	30 to 60	70 to 75
Darkroom	Negative	2	10	Yes[j]	No	—	—
Laboratory, general[y]	Negative	2	6	Yes	No	30 to 60	70 to 75
Laboratory, bacteriology	Negative	2	6	Yes	No	30 to 60	70 to 75
Laboratory, biochemistry[y]	Positive	2	6	—	No	30 to 60	70 to 75
Laboratory, cytology	Negative	2	6	Yes	No	30 to 60	70 to 75
Laboratory, glasswashing	Negative	Optional	10	Yes	—	—	—
Laboratory, histology	Negative	2	6	Yes	No	30 to 60	70 to 75
Microbiology[y]	Negative	—	6	Yes	No	30 to 60	70 to 75
Laboratory, nuclear medicine	Negative	2	6	Yes	No	30 to 60	70 to 75
Laboratory, pathology	Negative	2	6	Yes	No	30 to 60	70 to 75
Laboratory, serology	Positive	2	6	Yes	No	30 to 60	70 to 75
Laboratory, sterilizing	Negative	Optional	10	Yes	No	30 to 60	70 to 75
Laboratory, media transfer	Positive	2	4	—	No	30 to 60	70 to 75
Autopsy room[q]	Negative	2	12	Yes	No	—	—
Nonrefrigerated body-holding room[k]	Negative	Optional	10	Yes	No	—	70 to 75
Pharmacy	Positive[aa]	2	4	—	—	30 to 60	70 to 75
Administration							
Admitting and Waiting Rooms	Negative	2	6	Yes	—	30 to 60	70 to 75
Diagnostic and Treatment							
Bronchoscopy, sputum collection, and pentamidine administration	Negative	2	12	Yes	—	30 to 60	70 to 75
Examination room	—*	2	6	—	—	30 to 60	70 to 75
Medication room	Positive	2	4	—	—	30 to 60	70 to 75
Treatment room	—*	2	6	—	—	30 (W), 50 (S)	75 ± 2
Physical therapy and hydrotherapy	Negative	2	6	—	—	30 to 60	72 to 78 up to 80
Soiled workroom or soiled holding	Negative	2	10	Yes	No	30 to 60	72 to 78
Clean workroom or clean holding	Positive	2	4	—	—	—	—
Sterilizing and Supply							
ETO-sterilizer room	Negative	—	10	Yes	No	30 to 60	72 to 78
Sterilizer equipment room	Negative	—	10	Yes	No	30 to 60	74 ± 2
Central medical and surgical supply							
Soiled or decontamination room	Negative	2	6	Yes	No	30 to 60	72 to 78
Clean workroom	Positive	2	4	—	No	30 to 60	72 to 78
Sterile storage	Positive	2	4	—	—	Under 50	74 ± 2
Endoscope cleaning room	Negative	2	10	Yes	No	—	—

Table 3 Ventilation Requirements for Areas Affecting Patient Care in Hospitals and Outpatient Facilities (*Continued*)

Function Space	Pressure Relationship to Adjacent Areas[a]	Minimum Air Changes of Outside Air per Hour[b]	Minimum Total Air Changes per Hour[c]	All Air Exhausted Directly to Outside[m]	Air Recirculated Within Room Units[d]	Relative Humidity,[n] %	Design Temperature,[o] °F
Service							
Food preparation center[l]	—*	2	10	Yes	No	—	—
Warewashing	Negative	Optional	10	Yes	No	—	—
Dietary day storage	*	Optional	2	—	No	—	—
Laundry, general	Negative	2	10	Yes	No	—	—
Soiled linen sorting and storage	Negative	Optional	10	Yes	No	—	—
Clean linen storage	Positive	2 (Optional)	2	—	—	—	—
Linen and trash chute room	Negative	Optional	10	Yes	No	—	—
Bedpan room	Negative	Optional	10	Yes	No	—	—
Bathroom	Negative	Optional	10	Yes	No	—	72 to 78
Janitor's closet	Negative	Optional	10	Yes	No	—	—
Hazardous material storage	Negative	2	10	Yes	No	—	—

(W) = winter   (S) = summer

* = Continuous directional control not required

[a] Where continuous directional control is not required, variations should be minimized; in no case should a lack of directional control allow spread of infection from one area to another. Boundaries between functional areas (wards or departments) should have directional control. Lewis (1988) describes ways to maintain directional control by applying air-tracking controls. Ventilation system design should provide air movement, generally from clean to less clean areas. If any VAV or load-shedding system is used for energy conservation, it must not compromise pressure-balancing relationships or minimum air changes required by the table. See note z for additional information.

[b] Ventilation rates in this table cover ventilation for comfort, as well as for asepsis and odor control in areas of acute-care hospitals that directly affect patient care. Ventilation rates in accordance with ASHRAE *Standard* 62, Ventilation for Acceptable Indoor Air Quality, should be used for areas for which specific ventilation rates are not given. Where a higher outside air requirement is called for in *Standard* 62 than here, use the higher value.

[c] Total air changes indicated should be either supplied or, where required, exhausted. Number of air changes can be reduced when the room is unoccupied, if the pressure relationship is maintained and the number of air changes indicated is reestablished any time the space is used. Air changes shown are minimum values. Higher values should be used when required to maintain room temperature and humidity conditions based on the cooling load of the space (lights, equipment, people, exterior walls and windows, etc.).

[d] Recirculating HEPA filter units used for infection control (without heating or cooling coils) are acceptable. Gravity-type heating or cooling units such as radiators or convectors should not be used in operating rooms and other special-care areas.

[e] For operating rooms, 100% outside air should be used only when codes require it and only if heat recovery devices are used.

[f] "Trauma room" here is a first-aid room and/or emergency room used for general initial treatment of accident victims. The operating room in the trauma center that is routinely used for emergency surgery should be treated as an operating room.

[g] See section on Patient Rooms for discussion of central toilet exhaust system design.

[h] "Airborne infectious isolation rooms" here are those that might be used for infectious patients in the average community hospital. The rooms are negatively pressurized. Some may have a separate anteroom. See the section on Infectious Isolation Unit for more information.

[i] Protective-environment rooms are those used for immunosuppressed patients, positively pressurized to protect the patient. Anterooms are generally required and should be negatively pressurized with respect to the patient room.

[j] All air need not be exhausted if darkroom equipment has scavenging exhaust duct attached and meets ventilation standards of NIOSH, OSHA, and local employee exposure limits.

[k] A nonrefrigerated body-holding room is only applicable to facilities that do not perform autopsies onsite and use the space for short periods while waiting for the body to be transferred.

[l] Food preparation centers should have an excess of air supply for positive pressurization when hoods are not in operation. The number of air changes may be reduced or varied for odor control when the space is not in use. Minimum total air changes per hour should be that required to provide proper makeup air to kitchen exhaust systems. (See Chapter 31, Kitchen Ventilation.) Also, exfiltration or infiltration to or from exit corridors must not compromise exit corridor restrictions of NFPA *Standard* 90A, pressure requirements of NFPA *Standard* 96, or the maximum defined in the table. The number of air changes may be reduced or varied as required for odor control when the space is not in use. See AIA (2006), Table 2.1.2.

[m] Areas with contamination and/or odor problems should be exhausted to the outside and not recirculated to other areas. Individual circumstances may require special consideration for air exhaust to the outside (e.g., intensive care units where patients with pulmonary infection are treated, rooms for burn patients). To satisfy exhaust needs, replacement air from the outside is necessary. Minimum outside air quantities should remain constant while the system is in operation.

[n] Relative humidity ranges listed are minimum and maximum limits where control is specifically needed. These limits are not intended to be independent of space temperature. For example, relative humidity is expected to be at the higher end of the range when the temperature is also at the higher end, and vice versa.

[o] For indicated temperature ranges, systems should be capable of maintaining the rooms at any point within the range during normal operation. A single figure indicates a heating or cooling capacity to at least meet the indicated temperature. This is usually applicable when patients may be undressed and require a warmer environment. Use of lower temperature is acceptable when patients' comfort and medical conditions require those conditions.

[p] NIOSH *Criteria Documents* 75-137 and 96-107 on waste anesthetic gases and nitrous oxide indicate a need for both local exhaust (scavenging) systems and general ventilation of areas in which these gases are used.

[q] Differential pressure between space and corridors should be a minimum of 0.01 in. of water. If monitoring device alarms are installed, allowances should be made to prevent nuisance alarms.

[r] Because some surgeons or surgical procedures may require room temperatures outside the indicated range, operating room design conditions should be developed in consort with all users, surgeons, anesthesiologists, and nursing staff.

[s] The first-aid and/or emergency room used for initial treatment of accident victims can be ventilated as for the treatment room. Treatment rooms used for cryosurgery with nitrous oxide should have provisions for exhausting waste gases.

[t] In a recirculating ventilation system, HEPA filters can be used instead of exhausting the air to the outside; return air should pass through the HEPA filters before being introduced to any other spaces.

[u] If exhausting air from an airborne-infection isolation room to the outside is not practical, the air may be returned through HEPA filters to the air-handling system exclusively serving the isolation room.

[v] Total air changes per room for patient rooms, and labor/delivery/recovery/postpartum rooms may be reduced to four when using supplemental heating and/or cooling systems (radiant heating and cooling, baseboard heating, etc.).

[w] Protective-environment airflow design specifications protect the patient from common environmental airborne infectious microbes (e.g., *Aspergillus* spores). They should provide directed airflow from the cleanest patient area to less clean areas. HEPA filters at 99.9% efficiency to 0.3 μm should be used in the supply airstream, to protect patient rooms from environmental microbes in ventilation system components. Recirculation HEPA filters can be used to increase equivalent room air exchanges. Constant-volume airflow is required for consistent ventilation. If design criteria indicate that airborne-infection isolation is necessary for protective-environment patients, an anteroom should be provided. Rooms with reversible airflow provisions (to allow switching between protective-environment and airborne-infection isolation) are not acceptable (AIA 2006).

[x] "Infectious disease isolation (AII) room" here is one used to isolate the airborne spread of infectious diseases, such as measles, varicella, or tuberculosis. Design should include provision for normal patient care during periods not requiring isolation. Supplemental recirculating devices may be used in the patient room to increase the equivalent room air exchanges; however, they do not provide outside air requirements. Air may be recirculated within individual isolation rooms if HEPA filters are used. Rooms with reversible airflow provisions (to allow switching between protective-environment and AII) are not acceptable (AIA 2006).

[y] When required, provide appropriate hoods and exhaust devices for noxious gases or vapors [AIA (2006), see Section 2.1-10.2.4.5(2), and NFPA *Standard* 99).

[z] Simple visual methods such as smoke trail, ball-in-tube, or flutterstrip can be used to verify airflow direction. These devices require a minimum differential air pressure to indicate airflow direction. Per AIA (2006) guidelines, recirculating devices with HEPA filters may be used in existing facilities as interim, supplemental environmental controls to meet requirements for airborne infectious agents control. Design limitations must be recognized. Either portable or fixed systems should prevent stagnation and short-circuiting of airflow. Supply and exhaust locations should direct clean air to work areas across the infectious source, and then to the exhaust, so that health care workers are not positioned between the infectious source and the exhaust. Systems design should also allow easy access for scheduled preventative maintenance and cleaning.

[aa] Some jurisdictions may require pharmacies that compound hazardous drugs to be maintained under negative pressure or use anterooms to reduce the potential migration of airborne drug contamination out of the pharmacy.

[ab] Consult user for standard of care expectation, because space could be also be considered negative or positive.

Recovery Rooms. Postoperative recovery rooms used in conjunction with operating rooms should be maintained at a relative humidity of 45 to 55%. Because the smell of residual anesthesia sometimes creates odor problems in recovery rooms, ventilation is important, and a balanced air pressure relative to that of adjoining areas should be provided.

Intensive Care Units. These units serve seriously ill patients, from postoperative to coronary patients. A variable-range temperature capability of 70 to 75°F, relative humidity of 30% minimum and 60% maximum, and positive air pressure are recommended.

Nursery Suites. Air conditioning in nurseries provides the constant temperature and humidity conditions essential to care of the newborn in a hospital environment. Air movement patterns in nurseries should be carefully designed to reduce the possibility of drafts.

Some codes or jurisdictions require that air be removed near floor level, with the bottoms of exhaust openings at least 3 in. above the floor; the relative efficacy of this exhaust arrangement has been questioned by some experts, because exhaust air outlets have a minimal effect on room air movement at the relatively low air exchange rates involved. Air system filter efficiencies should conform to Table 1. Finned tube radiation and other forms of convection heating should not be used in nurseries.

Full-Term Nurseries. A relative humidity of 30 to 60% is recommended for full-term nurseries, examination rooms, and work spaces. The maternity nursing section should be controlled similarly to protect the infant during visits with the mother. The nursery should have a positive air pressure relative to the work space and examination room, and any rooms located between the nurseries and the corridor should be similarly pressurized relative to the corridor. This prevents infiltration of contaminated air from outside areas.

Special-Care Nurseries. These nurseries require a variable range temperature capability of 75 to 80°F and a relative humidity of 30 to 60%. This type of nursery is usually equipped with individual incubators to regulate temperature and humidity. It is desirable to maintain these same conditions within the nursery proper to accommodate both infants removed from the incubators and those not placed in incubators. Pressurization of special-care nurseries should correspond to that of full-term nurseries.

Observation Nurseries. Temperature and humidity requirements for observation nurseries are similar to those for full-term nurseries. Because infants in these nurseries have unusual clinical symptoms, the air from this area should not enter other nurseries. A negative air pressure relative to that of the workroom should be maintained in the nursery. The workroom, usually located between the nursery and the corridor, should be pressurized relative to the corridor.

Emergency Rooms. Emergency rooms are typically the most highly contaminated areas in the hospital because of the soiled condition of many arriving patients and the relatively large number of persons accompanying them. Temperatures and humidities of offices and waiting spaces should be within the normal comfort range.

Trauma Rooms. Trauma rooms should be ventilated in accordance with requirements in Table 3. Emergency operating rooms located near the emergency department should have the same temperature, humidity, and ventilation requirements as those of operating rooms.

Anesthesia Storage Rooms. Anesthesia storage rooms must be ventilated in conformance with NFPA *Standard* 99. However, mechanical ventilation only is recommended.

Nursing

Patient Rooms. When central systems are used to condition patient rooms, recommendations in Tables 1 and 3 should be followed to reduce cross-infection and control odor. Each patient room should have individual temperature control. Air pressure in patient suites should be neutral in relation to other areas.

Most governmental design criteria and codes require that all air from toilet rooms be exhausted directly outside. The requirement appears to be based on odor control.

Where room unit systems are used, it is common practice to exhaust through the adjoining toilet room an amount of air equal to the amount of outside air brought in for ventilation. Ventilation of toilets, bedpan closets, bathrooms, and all interior rooms should conform to applicable codes.

Protective Isolation Units. Immunosuppressed patients (including bone marrow or organ transplant, leukemia, burn, and AIDS patients) are highly susceptible to diseases. Some physicians prefer an isolated laminar airflow unit to protect the patient; others are of the opinion that the conditions of the laminar cell have a psychologically harmful effect on the patient and prefer flushing out the room and reducing spores in the air. An air distribution of 15 air changes per hour supplied through a nonaspirating diffuser is often recommended. With this arrangement, the sterile air is drawn across the patient and returned near the floor, at or near the door to the room.

In cases where the patient is immunosuppressed but not contagious, positive pressure should be maintained between the patient room and adjacent area. Some jurisdictions may require an anteroom, which maintains a negative pressure relative to the adjacent isolation room and an equal pressure to the corridor, nurses' station, or common area. Exam and treatment rooms should be controlled in the same manner. Positive pressure should also be maintained between the entire unit and adjacent areas to preserve sterile conditions.

When a patient is both immunosuppressed and contagious, isolation rooms within the unit may be designed and balanced to provide a permanent equal or negative pressure relative to the adjacent area or anteroom. Pressure controls in the adjacent area or anteroom must maintain the correct pressure relationship relative to the other adjacent room(s). A separate, dedicated air-handling system to serve the protective isolation unit simplifies pressure control and quality (Murray et al. 1988).

Infectious Isolation Unit. The infectious isolation room protects the rest of the hospital from patients' infectious diseases. Recent multidrug-resistant strains of tuberculosis have increased the importance of pressurization, air change rates, filtration, and air distribution design in these rooms (Rousseau and Rhodes 1993). Temperatures and humidities should correspond to those specified for patient rooms.

The designer should work closely with health care planners and the code authority to determine the appropriate isolation room design. It may be desirable to provide more complete control, with a separate anteroom used as an air lock to minimize the potential that airborne particles from the patients' area reach adjacent areas. Design approaches to airborne infectious isolation may also be found in CDC (2005).

Switchable isolation rooms (rooms that can be set to function with either positive or negative pressure) have been installed in many facilities. AIA (2006) and CDC (1994) have, respectively, prohibited and recommend against this approach. The two difficulties of this approach are (1) maintaining the mechanical dampers and controls required to accurately provide the required pressures, and (2) that it provides a false sense of security to staff who think that this provision is all that is required to change a room between protective isolation and infectious isolation, to the exclusion of other sanitizing procedures.

Floor Pantry. Ventilation requirements for this area depend on the type of food service adopted by the hospital. Where bulk food is dispensed and dishwashing facilities are provided in the pantry, using hoods above equipment, with exhaust to the outside, is recommended. Small pantries used for between-meal feedings require no special ventilation. The air pressure of the pantry should be in balance with that of adjoining areas to reduce the movement of air into or out of it.

Labor/Delivery/Recovery/Postpartum (LDRP). The procedures for normal childbirth are considered noninvasive, and rooms are controlled similarly to patient rooms. Some jurisdictions may require higher air change rates than in a typical patient room. It is expected that invasive procedures such as cesarean section are performed in a nearby delivery or operating room.

Ancillary

Radiology Department. Among the factors affecting ventilation system design in these areas are odors from certain clinical treatments and the special construction designed to prevent radiation leakage. Fluoroscopic, radiographic, therapy, and darkroom areas require special attention.

Fluoroscopic, Radiographic, and Deep Therapy Rooms. These rooms require a temperature from 78 to 80°F and a relative humidity from 40 to 50%. This relative humidity range control often requires dedicated room equipment and control. Depending on the location of air supply outlets and exhaust intakes, lead lining may be required in supply and return ducts at points of entry to various clinical areas to prevent radiation leakage to other occupied areas.

Darkroom. The darkroom is normally in use for longer periods than x-ray rooms, and should have an independent system to exhaust air to the outside. Exhaust from the film processor may be connected into the darkroom exhaust.

Laboratories. Air conditioning is necessary in laboratories for the comfort and safety of the technicians (Degenhardt and Pfost 1983). Chemical fumes, odors, vapors, heat from equipment, and the undesirability of open windows all contribute to this need.

Particular attention should be given to the size and type of equipment used in the various laboratories, as equipment heat gain usually constitutes a major portion of the cooling load.

The general air distribution and exhaust systems should be constructed of conventional materials following standard designs for the type of systems used. Exhaust systems serving hoods in which radioactive materials, volatile solvents, and strong oxidizing agents such as perchloric acid are used should be made of stainless steel. Washdown facilities and dedicated exhaust fans should be provided for hoods and ducts handling perchloric acid.

Hood use may dictate other duct materials. Hoods in which radioactive or infectious materials are to be used must be equipped with ultrahigh-efficiency filters at the exhaust outlet and have a procedure and equipment for safe removal and replacement of contaminated filters. Exhaust duct routing should be as short as possible with minimal horizontal offsets. This applies especially to perchloric acid hoods because of the extremely hazardous, explosive nature of this material.

Determining the most effective, economical, and safe system of laboratory ventilation requires considerable study. Where laboratory space ventilation air quantities approximate the air quantities required for ventilating the hoods, the hood exhaust system may be used to exhaust all ventilation air from the laboratory areas. Where hood exhaust exceeds air supplied, a supplementary air supply may be used for hood makeup. VAV supply/exhaust systems in the laboratory have gained acceptance but require special care in design and installation.

Supplementary air supply, which need not be completely conditioned, should be provided by a system independent of the normal ventilating system. The individual hood exhaust system should be interlocked with the supplementary air system. However, the hood exhaust system should not shut off if the supplementary air system fails. Chemical storage rooms must have a constantly operating exhaust air system with a terminal fan.

Hood exhaust fans should be located at the discharge end of the duct system to prevent exhaust products entering the building. For further information on laboratory air conditioning and hood exhaust systems, see NFPA *Standard* 99, Hagopian and Hoyle (1984), and Chapter 14 of this volume.

Exhaust air from hoods in biochemistry, histology, cytology, pathology, glass washing/sterilizing, and serology-bacteriology units should be discharged to the outside with no recirculation. Use care in designing the exhaust outlet locations and arrangements: exhaust should not be re-entrained in the building via outside air intakes or other building openings. Separation from outside air intake sources, wind direction and velocity, building geometry, and exhaust outlet height and velocity are important. In some laboratory exhaust systems, exhaust fans discharge vertically at a minimum of 7 ft above the roof at velocities up to 4000 fpm. The serology-bacteriology unit should be positively pressured relative to adjoining areas to reduce the possibility of infiltration of aerosols that could contaminate the specimens being processed. The entire laboratory area should be under slight negative pressure to reduce the spread of odors or contamination to other hospital areas. Temperatures and humidities should be within the comfort range.

Bacteriology Laboratories. These units should not have undue air movement, so care should be exercised to limit air velocities to a minimum. The sterile transfer room, which may be within or adjoining the bacteriology laboratory, is where sterile media are distributed and where specimens are transferred to culture media. To maintain a sterile environment, an ultrahigh-efficiency HEPA filter should be installed in the supply air duct near the point of entry to the room. The media room, essentially a kitchen, should be ventilated to remove odors and steam.

Infectious Disease and Virus Laboratories. These laboratories, found only in large hospitals, require special treatment. A minimum ventilation rate of 6 air changes per hour or makeup equal to hood exhaust volume is recommended for these laboratories, which should have a negative air pressure relative to any other area nearby to prevent exfiltration of any airborne contaminants. Exhaust air from fume hoods or safety cabinets must be sterilized before being exhausted to the outside. This may be accomplished by using electric or gas-fired heaters placed in series in the exhaust systems and designed to heat the exhaust air to 600°F. A more common and less expensive method of sterilizing the exhaust is to use HEPA filters in the system.

Nuclear Medicine Laboratories. Such laboratories administer radioisotopes to patients orally, intravenously, or by inhalation to facilitate diagnosis and treatment of disease. There is little opportunity in most cases for airborne contamination of the internal environment, but exceptions warrant special consideration.

One important exception involves the use of iodine-131 solution in capsules or vials to diagnose thyroid disorders. Another involves use of xenon-133 gas via inhalation to study patients with reduced lung function.

Capsules of iodine-131 occasionally leak part of their contents prior to use. Vials emit airborne contaminants when opened for preparation of a dose. It is common practice for vials to be opened and handled in a standard laboratory fume hood. A minimum face velocity of 100 fpm should be adequate for this purpose. This recommendation applies only where small quantities are handled in simple operations. Other circumstances may warrant provision of a glove box or similar confinement.

Use of xenon-133 for patient study involves a special instrument that permits the patient to inhale the gas and to exhale back into the instrument. The exhaled gas is passed through a charcoal trap mounted in lead and is often vented outside. The process suggests some potential for escape of the gas into the internal environment.

Because of the uniqueness of this operation and the specialized equipment involved, it is recommended that system designers determine the specific instrument to be used and contact the manufacturer for guidance. Other guidance is available in U.S. Nuclear Regulatory Commission *Regulatory Guide* 10.8 (NRC 1980). In particular, emergency procedures in case of accidental release of

xenon-133 should include temporary evacuation of the area and/or increasing the ventilation rate of the area.

Recommendations for pressure relationships, supply air filtration, supply air volume, recirculation, and other attributes of supply and discharge systems for histology, pathology, and cytology laboratories are also relevant to nuclear medicine laboratories. There are, however, some special ventilation system requirements imposed by the NRC where radioactive materials are used. For example, NRC (1980) provides a computational procedure to estimate the airflow necessary to maintain xenon-133 gas concentration at or below specified levels. It also contains specific requirements as to the amount of radioactivity that may be vented to the atmosphere; the disposal method of choice is adsorption onto charcoal traps.

Autopsy Rooms. Susceptible to heavy bacterial contamination (e.g., tuberculosis) and odor, autopsy rooms, which are part of the hospital's pathology department, require special attention. Exhaust intakes should be located both at the ceiling and in the low sidewall. The exhaust system should discharge the air above the roof of the hospital, away from points of potential reentrainment, such as outside air intakes and building openings. The autopsy room should be negatively pressured relative to adjoining areas to prevent the spread of contamination. Where large quantities of formaldehyde are used, special exhaust systems can effectively control concentrations below legal exposure limits. A combination of localized exhaust and ventilation systems with downdraft or side-draft tables can also effectively control concentrations while using smaller exhaust volumes than those required by dilution ventilation.

In smaller hospitals where the autopsy room is used infrequently, local control of the ventilation system and an odor control system with either activated charcoal or potassium permanganate-impregnated activated alumina may be desirable.

Animal Quarters. Principally because of odor, animal quarters (found only in larger hospitals) require a mechanical exhaust system that discharges contaminated air above the hospital roof. To prevent the spread of odor or other contaminants from the animal quarters to other areas, a negative air pressure of at least 0.1 in. of water relative to adjoining areas must be maintained. Chapter 14 has further information on animal room air conditioning.

Pharmacies. Design and ventilation requirements for pharmacies can vary greatly according to the type of compounding done there. Pharmacies handling hazardous drugs and/or involved in sterile compounding activities have special ventilation requirements such as, for example, horizontal or vertical laminar-airflow workbenches (LAFW), biological safety cabinets (BSC), and compounding (barrier) isolators. Room air distribution and filtration must be coordinated with any laminar airflow benches, cabinets, and isolators that may be needed. See Chapters 14 and 16 for more information.

Sterile Compounding. Sterile pharmaceutical compounding requirements are prescribed by the U.S. Pharmacopeia (USP 2003). This chapter is enforceable under the U.S. Food and Drug Administration, is adopted in whole or in part by many state boards of pharmacy, and may be incorporated into the inspection programs of health care accreditation organizations such as the Joint Commission on Accreditation of Healthcare Organization (JCAHO). End users, owners, architects, and engineers should consult the most recent release of USP 797, which is under continuous maintenance, as well as design guidance adopted by their state boards of pharmacy.

USP 797 prescribes that all sterile pharmaceutical preparations be compounded entirely within a critical work zone of ISO class 5 (former class 100 under Federal Standard 209E) or better air quality. This class 5 environment is generally provided using a primary engineering control. USP 797 also requires that the ISO class 5 critical work zone be placed in a buffer zone (also called a buffer room or cleanroom) whose air quality must meet a minimum of ISO class 8 and contain air-conditioning and humidity controls. [*Note*: In late 2004, USP announced its intention to increase the minimum air quality in the buffer zone to ISO class 7 (Newton 2004).] Lastly, adjacent to the buffer area, the sterile compounding pharmacy design must incorporate an anteroom for storage, hand washing, non-sterile preparation activities, donning and doffing of protective overgarments, etc. The air cleanliness in the anteroom must be ". . . demonstrably better than that of ambient air to reduce the risk of contaminants being blown, dragged or otherwise introduced into the filtered unidirectional airflow environment" (USP 2003).

Beyond air quality requirements, the physical design features separating the buffer area from the anteroom are based on the pharmacy's compounded sterile preparation (CSP) risk level (low, medium, or high) for microbial, chemical, and physical contamination. USP 797 instructs pharmacy professionals on determination of their pharmacy's CSP risk level based on purity and packaging of source materials, quantity and type of pharmaceutical, time until its administration, and various other factors. The desired CSP risk level capability should be identified before initiating the pharmacy design layout. Pharmacies intended for compounding high-risk-level CSPs require a physical barrier with a door to separate the buffer room from the anteroom. For medium- and low-risk level CSPs, the buffer area and anteroom can be in the same room, with an obvious line of demarcation separating the two areas (USP 2003).

Hazardous Drugs. In addition to defining and listing hazardous drugs, the NIOSH Alert provides protective recommendations, several of which can affect the ventilation design and physical layout of the pharmacy. These recommendations include the following:

- Prepare hazardous drugs in an area devoted to that purpose alone and restricted to authorized personnel.
- Prepare hazardous drugs inside a ventilated cabinet designed to prevent hazardous drugs from being released into the work environment.
- Use a high-efficiency particulate air (HEPA) filter for exhaust from ventilated cabinets and, where feasible, exhaust 100% of the filtered air to the outside, away from outside air intakes or other points of entry.
- Place fans downstream of HEPA filters so that contaminated ducts and plenums are maintained under negative pressure.
- Do not use ventilated cabinets that recirculate air inside the cabinet or that exhaust air back into the pharmacy unless the hazardous drug(s) in use will not volatilize (evaporate or sublimate) while they are being handled or after they are captured by the HEPA filter. (*Note*: This recommendation is a shift from traditional pharmacy design practice and involves knowledge of the physical properties of drugs within the current drug formulary as well as future new drugs that might be compounded within the cabinet.)
- Store hazardous drugs separately from other drugs, in an area with sufficient general exhaust ventilation to dilute and remove any airborne contaminants. Depending on the physical nature and quantity of the stored drugs, consider installing a dedicated emergency exhaust fan capable of quickly purging airborne contaminants from the storage room in the event of a spill, to prevent airborne migration into adjacent areas.

In December 2005, the American Society of Health Systems Pharmacists (ASHP) released a prepublication version of their *ASHP Guidelines on Handling Hazardous Drugs*. In addition to adopting the protective equipment recommendations presented in the NIOSH Alert, the ASHP *Guidelines* recommend that hazardous drug compounding be done in a contained, negative-pressure environment or one that is protected by an airlock or anteroom (ASHP 2005).

Often, the hazardous drugs previously discussed also require sterile compounding. If so, pharmacies must have an environment

Table 4   Minimum Environmental Control Requirements for Pharmacies

Compounding Scenario	Hazardous Drug (HD) (Requires separate area)	Nonhazardous Drug
Sterile compounding (Requires particle-controlled environment)	If no particle-controlled environment, needs ISO 5 compounding aseptic containment isolator or If ISO 8* or better environment, needs ISO 5 compounding aseptic containment isolator, Class II BSC or Class III BSC. [Physically-separated buffer (clean) room required if CSP risk level is rated high]	If no particle-controlled environment, needs ISO 5 compounding aseptic isolator or If ISO 8* or better environment, needs ISO 5 laminar airflow workbench or Class II BSC [Physically-separated buffer (clean) room required if CSP risk level is rated high]
Nonsterile compounding	Needs compounding containment isolator or BSC	No sterility or occupational exposure controls required

*The USP Sterile Compounding Committee has indicated its intention to increase the minimum air particle count classification for the buffer area to ISO Class 7.

suitable for both product sterility and worker protection. Both the NIOSH Alert and ASHP *Guidelines on Hazardous Drugs* address these dual objectives by recommending the use of class II or class III BSCs or compounding aseptic containment isolators. The precautionary recommendations regarding in-cabinet recirculation and cabinet-to-room recirculation of air potentially contaminated with hazardous drugs still apply. In addition, the USP's Sterile Compounding Committee, responsible for maintaining USP 797, has announced its intent to address the issue of hazardous drug sterile compounding in an updated release of USP 797, partially through reference to the NIOSH Alert (Newton 2004).

Table 4 provides a matrix of design and equipment decision logic based on USP 797 and the NIOSH Alert on Hazardous Drugs.

Administration

This department includes the main lobby and admitting, medical records, and business offices. Admissions and waiting rooms harbor potential risks of transmitting of undiagnosed airborne infectious diseases. Local exhaust systems that move air toward the admitting patient should be considered. A separate air-handling system is considered desirable to segregate this area from the hospital proper because it is usually unoccupied at night. When interior architectural open-water features are proposed, water treatment to protect occupants from infectious or irritating aerosols should be provided.

Diagnostic and Treatment

Bronchoscopy, Sputum Collection, and Pentamidine Administration Areas. These spaces are remarkable due to the high potential for large discharges of possibly infectious water droplet nuclei into the room air. Although the procedures performed may indicate the use of a patient hood, the general room ventilation should be increased under the assumption that higher than normal levels of airborne infectious contaminants will be generated.

Magnetic Resonance Imaging (MRI) Rooms. These rooms should be treated as exam rooms in terms of temperature, humidity, and ventilation. However, special attention is required in the control room because of the high heat release of computer equipment; in the exam room, because of the cryogens used to cool the magnet.

Treatment Rooms. Patients are brought to these rooms for special treatments that cannot be conveniently administered in the patients' rooms. To accommodate the patient, who may be brought from bed, the rooms should have individual temperature and humidity control. Temperatures and humidities should correspond to those specified for patients' rooms.

Physical Therapy Department. The cooling load of the electrotherapy section is affected by the shortwave diathermy, infrared, and ultraviolet equipment used in this area.

Hydrotherapy Section. This section, with its various water treatment baths, is generally maintained at temperatures up to 80°F. The potential latent heat buildup in this area should not be overlooked. The exercise section requires no special treatment; temperatures and humidities should be within the comfort zone.

The air may be recirculated within the areas, and an odor control system is suggested.

Occupational Therapy Department. In this department, spaces for activities such as weaving, braiding, artwork, and sewing require no special ventilation treatment. Air recirculation in these areas using medium-grade filters in the system is permissible.

Larger hospitals and those specializing in rehabilitation may offer patients a greater diversity of skills to learn and craft activities, including carpentry, metalwork, plastics, photography, ceramics, and painting. The air-conditioning and ventilation requirements of the various sections should conform to normal practice for such areas and to the codes relating to them. Temperatures and humidities should be maintained in the comfort zone.

Inhalation Therapy Department. This department treats pulmonary and other respiratory disorders. The air must be very clean, and the area should have a positive pressure relative to adjacent areas.

Workrooms. Clean workrooms serve as storage and distribution centers for clean supplies and should be maintained at a positive pressure relative to the corridor.

Soiled workrooms serve primarily as collection points for soiled utensils and materials. They are considered contaminated rooms and should have a negative air pressure relative to adjoining areas. Temperatures and humidities should be in the comfort range.

Sterilizing and Supply

Used and contaminated utensils, instruments, and equipment are brought to this unit for cleaning and sterilization before reuse. The unit usually consists of a cleaning area, a sterilizing area, and a storage area where supplies are kept until requisitioned. If these areas are in one large room, air should flow from the clean storage and sterilizing areas toward the contaminated cleaning area. The air pressure relationships should conform to those indicated in Table 3. Temperature and humidity should be within the comfort range.

The following guidelines are important in the central sterilizing and supply unit:

- Insulate sterilizers to reduce heat load.
- Amply ventilate sterilizer equipment closets to remove excess heat.
- Where ethylene oxide (ETO) gas sterilizers are used, provide a separate exhaust system with terminal fan (Samuals and Eastin 1980). Provide adequate exhaust capture velocity in the vicinity of sources of ETO leakage. Install an exhaust at sterilizer doors and over the sterilizer drain. Exhaust aerator and service rooms. ETO concentration sensors, exhaust flow sensors, and alarms should also be provided. ETO sterilizers should be located in dedicated unoccupied rooms that have a highly negative pressure relative to adjacent spaces and 10 air changes per hour. Many jurisdictions require that ETO exhaust systems have equipment to remove ETO from exhaust air. See OSHA 29 CFR, Part 1910.
- Maintain storage areas for sterile supplies at a relative humidity of no more than 50%.

Service

Service areas include dietary, housekeeping, mechanical, and employee facilities. Whether these areas are conditioned or not,

adequate ventilation is important to provide sanitation and a wholesome environment. Ventilation of these areas cannot be limited to exhaust systems only; provision for supply air must be incorporated into the design. Such air must be filtered and delivered at controlled temperatures. The best-designed exhaust system may prove ineffective without an adequate air supply. Experience has shown that reliance on open windows results only in dissatisfaction, particularly during the heating season. Air-to-air heat exchangers in the general ventilation system offer possibilities for economical operation in these areas.

Supply connections for water-using equipment (e.g., ice machines) should be copper rather than plastic tubing and should be provided with floor drains or floor sinks. Avoid designs that may include dead-end risers or branches without fixtures; in renovation projects, dead-end piping should be removed. Empty or upsized risers or branches are viable options.

Dietary Facilities. These areas usually include the main kitchen, bakery, dietitian's office, dishwashing room, and dining space. Because of the various conditions encountered (i.e., high heat and moisture production and cooking odors), special attention in design is needed to provide an acceptable environment. Refer to Chapter 31 for information on kitchen facilities.

The dietitian's office is often located within the main kitchen or immediately adjacent to it. It is usually completely enclosed for privacy and noise reduction. Air conditioning is recommended for maintaining normal comfort conditions.

The dishwashing room should be enclosed and minimally ventilated to equal the dishwasher hood exhaust. It is not uncommon for the dishwashing area to be divided into a soiled area and a clean area. In such cases, the soiled area should be kept at a negative pressure relative to the clean area.

Ventilation of the dining space should conform to local codes. The reuse of dining space air for ventilation and cooling of food preparation areas in the hospital is suggested, provided the reused air is passed through filters with a filtration efficiency of MERV 13 or better. Where cafeteria service is provided, serving areas and steam tables are usually hooded. The air-handling capacities of these hoods should be sized to accommodate exhaust flow rates (see Table 2 in Chapter 31). Ventilation systems for food preparation and adjacent areas should include an interface with hood exhaust controls to assist in maintaining pressure relationships.

Kitchen Compressor/Condenser Spaces. Ventilation of these spaces should conform to all codes, with the following additional considerations: (1) 350 cfm of ventilating air per compressor horsepower should be used for units located within the kitchen; (2) condensing units should operate optimally at 90°F maximum ambient temperature; and (3) where air temperature or air circulation is marginal, combination air- and water-cooled condensing units should be specified. It is often worthwhile to use condenser water coolers or remote condensers. Heat recovery from water-cooled condensers should be considered.

Laundry and Linen Facilities. Of these facilities, only the soiled linen storage room, the soiled linen sorting room, the soiled utility room, and the laundry processing area require special attention.

The room for storing soiled linen before pickup by commercial laundry is odorous and contaminated, and should be well ventilated and maintained at a negative air pressure.

The soiled utility room is provided for inpatient services and is normally contaminated with noxious odors. This room should be exhausted directly outside by mechanical means.

In the laundry processing area, equipment such as washers, flatwork ironers, and tumblers should have direct overhead exhaust to reduce humidity. Such equipment should be insulated or shielded whenever possible to reduce the high radiant heat effects. A canopy over the flatwork ironer and exhaust air outlets near other heat-producing equipment capture and remove heat best. Air supply inlets should be located to move air through the processing area

toward the heat-producing equipment. The exhaust system from flatwork ironers and tumblers should be independent of the general exhaust system and equipped with lint filters. Air should exhaust above the roof or where it will not be obnoxious to occupants of other areas. Heat reclamation from the laundry exhaust air may be desirable and practicable.

Where air conditioning is contemplated, a separate supplementary air supply, similar to that recommended for kitchen hoods, may be located near the exhaust canopy over the ironer. Alternatively, spot cooling may be considered for personnel confined to specific areas.

Mechanical Facilities. The air supply to boiler rooms should provide both comfortable working conditions and the air quantities required for maximum combustion of the particular fuel used. Boiler and burner ratings establish maximum combustion rates, so the air quantities can be computed according to the type of fuel. Sufficient air must be supplied to the boiler room to supply the exhaust fans as well as the boilers.

At workstations, the ventilation system should limit temperatures to 90°F effective temperature. When ambient outside air temperature is higher, indoor temperature may be that of the outside air up to a maximum of 97°F to protect motors from excessive heat.

Maintenance Shops. Carpentry, machine, electrical, and plumbing shops present no unusual ventilation requirements. Proper ventilation of paint shops and paint storage areas is important because of fire hazard and should conform to all applicable codes. Maintenance shops where welding occurs should have exhaust ventilation.

CONTINUITY OF SERVICE AND ENERGY CONCEPTS

Zoning

Zoning (using separate air systems for different departments) may be indicated to (1) compensate for exposures because of orientation or for other conditions imposed by a particular building configuration, (2) minimize recirculation between departments, (3) provide flexibility of operation, (4) simplify provisions for operation on emergency power, and (5) conserve energy.

By ducting the air supply from several air-handling units into a manifold, central systems can achieve a measure of standby capacity. When one unit is shut down, air is diverted from noncritical or intermittently operated areas to accommodate critical areas, which must operate continuously. This or other means of standby protection is essential if the air supply is not to be interrupted by routine maintenance or component failure.

Separating supply, return, and exhaust systems by department is often desirable, particularly for surgical, obstetrical, pathological, and laboratory departments. The desired relative balance in critical areas should be maintained by interlocking supply and exhaust fans. Thus, exhaust should cease when supply airflow is stopped in areas otherwise maintained at positive or neutral pressure relative to adjacent spaces. Likewise, supply air should be deactivated when exhaust airflow is stopped in spaces maintained at a negative pressure.

Heating and Hot-Water Standby Service

The number and arrangement of boilers should be such that when one boiler breaks down or is temporarily taken out of service for routine maintenance, the capacity of the remaining boilers is sufficient to provide hot-water service for clinical, dietary, and patient use; steam for sterilization and dietary purposes; and heating for operating, delivery, birthing, labor, recovery, intensive care, nursery, and general patient rooms. However, reserve capacity may not be required in warmer climates, depending on individual facility building systems characteristics and operational requirements.

Some codes or authorities do not require reserve capacity in climates where a design dry-bulb temperature of 25°F is equaled or exceeded for 99.6% of the total hours in any one heating period as noted in the tables in Chapter 28 of the 2005 *ASHRAE Handbook—Fundamentals*.

Boiler feed, heat circulation, condensate return, and fuel oil pumps should be connected and installed to provide both normal and standby service. Supply and return mains and risers for cooling, heating, and process steam systems should be valved to isolate the various sections. Each piece of equipment should be valved at the supply and return ends.

Some supply and exhaust systems for delivery and operating room suites should be designed to be independent of other fan systems and to operate from the hospital emergency power system in the event of power failure. Operating and delivery room suites should be ventilated such that the hospital retains some surgical and delivery capability in cases of ventilating system failure.

Boiler steam is often treated with chemicals that cannot be released in the air-handling units serving critical areas. In this case, a clean steam system should be considered for humidification.

Mechanical Cooling

The source of mechanical cooling for clinical and patient areas in a hospital should be carefully considered. The preferred method is to use an indirect refrigerating system using chilled water or antifreeze solutions. When using direct refrigerating systems, consult codes for specific limitations and prohibitions. Refer to ASHRAE *Standard* 15, Safety Code for Mechanical Refrigeration.

Insulation

All exposed hot piping, ducts, and equipment should be insulated to maintain energy efficiency of all systems and protect building occupants. To prevent condensation, ducts, casings, piping, and equipment with outside surface temperature below ambient dew point should be covered with insulation having an external vapor barrier. Insulation, including finishes and adhesives on the exterior surfaces of ducts, pipes, and equipment, should have a flame spread rating of 25 or less and a smoke-developed rating of 50 or less, as determined by an independent testing laboratory in accordance with NFPA *Standard* 255, as required by NFPA 90A. The smoke-developed rating for pipe insulation should not exceed 150 (DHHS 1984).

Linings in air ducts and equipment should meet the erosion test method described in Underwriters Laboratories *Standard* 181. These linings, including coatings, adhesives, and insulation on exterior surfaces of pipes and ducts in building spaces used as air supply plenums, should have a flame spread rating of 25 or less and a smoke developed rating of 50 or less, as determined by an independent testing laboratory per ASTM *Standard* E84.

Duct linings should not be used in systems supplying operating rooms, delivery rooms, recovery rooms, nurseries, burn care units, or intensive care units, unless terminal filters of at least MERV 14 efficiency are installed downstream of linings. Duct lining should be used only for acoustical improvement; for thermal purposes, external insulation should be used.

When existing systems are modified, asbestos materials should be handled and disposed of per applicable regulations.

Energy

Health care is an energy-intensive, energy-dependent enterprise. Hospital facilities are different from other structures in that they operate 24 h/day year-round, require sophisticated back-up systems in case of utility shutdowns, use large quantities of outside air to combat odors and to dilute microorganisms, and must deal with problems of infection and solid waste disposal. Similarly, large quantities of energy are required to power diagnostic, therapeutic, and monitoring equipment; and support services such as food stor-

age, preparation, and service and laundry facilities. Control strategies such as supply air temperature reset on variable-air-volume systems and hydronic reheat supply water temperature reset on variable pumping systems can often be applied with good results.

Hospitals conserve energy in various ways, such as by using larger energy storage tanks and by using energy conversion devices that transfer energy from hot or cold building exhaust air to heat or cool incoming air. Heat pipes, runaround loops, and other forms of heat recovery are receiving increased attention. Solid waste incinerators, which generate exhaust heat to develop steam for laundries and hot water for patient care, are becoming increasingly common. Large health care campuses use central plant systems, which may include thermal storage, hydronic economizers, primary/secondary pumping, cogeneration, heat recovery boilers, and heat recovery incinerators.

The construction design of new facilities, including alterations of and additions to existing buildings, strongly influences the amount of energy required to provide services such as heating, cooling, and lighting. Selecting building and system components for effective energy use requires careful planning and design. Integrating building waste heat into systems and using renewable energy sources (e.g., solar under some climatic conditions) will provide substantial savings (Setty 1976).

Testing, Adjusting, and Balancing (TAB)

For existing systems, testing before the start of construction, preferably during design, can be a good investment. This early effort provides the designer with information on actual system performance and whether components are suitable for intended modifications, as well as disclosing additional modifications.

The importance of TAB for modified and new systems before patient occupancy cannot be overemphasized. Health care facilities require validation and documentation of system performance characteristics. Often, a combination of TAB with commissioning satisfies this requirement. See Chapters 37 and 42 for information on TAB and commissioning.

OUTPATIENT HEALTH CARE FACILITIES

An outpatient health care facility may be a free-standing unit, part of an acute care facility, or part of a medical facility such as a medical office building (clinic). Any surgery is performed without anticipation of overnight stay by patients (i.e., the facility operates 8 to 10 h per day).

If physically connected to a hospital and served by the hospital's HVAC systems, spaces within the outpatient health care facility should conform to requirements in the section on Hospital Facilities. Outpatient health care facilities that are totally detached and have their own HVAC systems may be categorized as diagnostic clinics, treatment clinics, or both.

DIAGNOSTIC CLINICS

A diagnostic clinic is a facility where patients are regularly seen on an ambulatory basis for diagnostic services or minor treatment, but where major treatment requiring general anesthesia or surgery is not performed. Diagnostic clinic facilities should be designed according to criteria shown in Tables 4 and 5 (see the section on Nursing Home Facilities).

TREATMENT CLINICS

A treatment clinic is a facility where major or minor procedures are performed on an outpatient basis. These procedures may render patients incapable of taking action for self-preservation under emergency conditions without assistance from others (NFPA *Standard* 101).

Design Criteria

The system designer should refer to the following paragraphs from the section on Hospital Facilities:

- Infection Sources and Control Measures
- Air Quality
- Air Movement
- Temperature and Humidity
- Pressure Relationships and Ventilation
- Smoke Control

Air-cleaning requirements correspond to those in Table 1 for operating rooms. A recovery area need not be considered a sensitive area. Infection control concerns are the same as in an acute care hospital. Minimum ventilation rates, desired pressure relationships and relative humidity, and design temperature ranges are similar to the requirements for hospitals shown in Table 3.

The following departments in a treatment clinic have design criteria similar to those in hospitals:

- Surgical: operating, recovery, and anesthesia storage rooms
- Ancillary
- Diagnostic and Treatment
- Sterilizing and Supply
- Service: soiled workrooms, mechanical facilities, and locker rooms

Continuity of Service and Energy Concepts

Some owners may desire standby or emergency service capability for the heating, air-conditioning, and service hot water systems and that these systems be able to function after a natural disaster.

To reduce utility costs, use energy-conserving measures such as recovery devices, variable air volume, load shedding, or devices to shut down or reduce ventilation of certain areas when unoccupied. Mechanical ventilation should take advantage of outside air by using an economizer cycle, when appropriate, to reduce heating and cooling loads.

The subsection on Continuity of Service and Energy Concepts in the section on Hospital Facilities includes information on zoning and insulation that applies to outpatient facilities as well.

NURSING FACILITIES

Nursing facilities may be classified as follows:

Extended care facilities are for recuperation of hospital patients who no longer require hospital facilities but do require the therapeutic and rehabilitative services of skilled nurses. This type of facility is either a direct hospital adjunct or a separate facility having close ties with the hospital. Clientele may be of any age, usually stay from 35 to 40 days, and usually have only one diagnostic problem.

Skilled nursing homes care for people who require assistance in daily activities; many of them are incontinent and nonambulatory, and some are disoriented. Residents may come directly from their homes or from residential care homes, are generally elderly (with an average age of 80), stay an average of 47 months, and frequently have multiple diagnostic problems.

Residential care homes are generally for elderly people who are unable to cope with regular housekeeping chores but have no acute ailments and are able to care for all their personal needs, lead normal lives, and move freely in and out of the home and the community. These homes may or may not offer skilled nursing care. The average length of stay is four years or more.

Functionally, these buildings have five types of areas that are of concern to the HVAC designer: (1) administrative and support areas inhabited by the staff, (2) patient areas that provide direct normal daily services, (3) treatment areas that provide special medical

Table 5 Filter Efficiencies for Central Ventilation and Air-Conditioning Systems in Nursing Facilities

Area Designation	Minimum Number of Filter Beds	Filter Efficiency of Main Filter Bed, MERV*
Resident care, treatment, diagnostic, and related areas	1	15
Food preparation areas and laundries	1	8
Administrative, bulk storage, and soiled holding areas	1	6

*Ratings based on ASHRAE *Standard* 52.2; MERV = Minimum Efficiency Reporting Value

services, (4) clean workrooms for storing and distributing clean supplies, and (5) soiled workrooms for collecting soiled and contaminated supplies and for sanitizing nonlaundry items.

DESIGN CONCEPTS AND CRITERIA

Controlling bacteria levels in nursing homes is not as critical as it is in acute care hospitals. Nevertheless, the designer should be aware of the necessity for odor control, filtration, and airflow control between certain areas.

Table 5 lists recommended filter efficiencies for air systems serving specific nursing home areas. Table 6 lists recommended minimum ventilation rates and desired pressure relationships for certain areas in nursing homes.

Recommended interior winter design temperature is 75°F for areas occupied by patients and 70°F for nonpatient areas. Provisions for maintenance of minimum humidity levels in winter depend on the severity of the climate and are best left to the judgment of the designer. Where air conditioning is provided, the recommended interior summer design temperature and humidity is 75°F and 50% rh.

The general design criteria in the sections on Heating and Hot-Water Standby Service, Insulation, and Energy for hospital facilities apply to nursing home facilities as well.

APPLICABILITY OF SYSTEMS

Nursing homes occupants are usually frail, and many are incontinent. Though some occupants are ambulatory, others are bedridden, suffering from the advanced stages of illnesses. The selected HVAC system must dilute and control odors and should not cause drafts. Local climatic conditions, costs, and designer judgment determine the extent and degree of air conditioning and humidification. Odor may be controlled with large volumes of outside air and some form of heat recovery. To conserve energy, odor may be controlled with activated carbon or potassium permanganate-impregnated activated alumina filters instead.

Temperature control should be on an individual-room basis. In geographical areas with severe climates, patients' rooms should have supplementary heat along exposed walls. In moderate climates (i.e., where outside winter design conditions are 30°F or above), heating from overhead may be used.

DENTAL CARE FACILITIES

Institutional dental facilities include reception and waiting areas, treatment rooms (called operatories), and workrooms where supplies are stored and instruments are cleaned and sterilized; they may include laboratories where restorations are fabricated or repaired.

Many common dental procedures generate aerosols, dusts, and particulates (Ninomura and Byrns 1998). The aerosols/dusts may contain microorganisms (both pathogenic and benign), metals (such as mercury fumes), and other substances (e.g., silicone dusts, latex allergens, etc.). Some measurements indicate that levels of bioaerosols during and immediately following a procedure can be extremely

Table 6   Pressure Relationships and Ventilation of Certain Areas of Nursing Facilities

Function Area	Pressure Relationship to Adjacent Areas	Minimum Air Changes of Outside Air per Hour Supplied to Room	Minimum Total Air Changes per Hour Supplied to Room	All Air Exhausted Directly to Outside	Air Recirculated Within Room Units
Resident Care					
Resident room (holding room)	*	2	4	Optional	Optional
Resident corridor	*	Optional	2	Optional	Optional
Toilet room	Negative	Optional	10	Yes	No
Resident gathering (dining, activity)	*	2	4	Optional	Optional
Diagnostic and Treatment					
Examination room	*	2	6	Optional	Optional
Physical therapy	Negative	2	6	Optional	Optional
Occupational therapy	Negative	2	6	Optional	Optional
Soiled workroom or soiled holding	Negative	2	10	Yes	No
Clean workroom or clean holding	Positive	2	4	Optional	Optional
Sterilizing and Supply					
Sterilizer exhaust room	Negative	Optional	10	Yes	No
Linen and trash chute room	Negative	Optional	10	Yes	No
Laundry, general	*	2	10	Yes	No
Soiled linen sorting and storage	Negative	Optional	10	Yes	No
Clean linen storage	Positive	Optional	2	Yes	No
Service					
Food preparation center	*	2	10	Yes	Yes
Warewashing room	Negative	Optional	10	Yes	Yes
Dietary day storage	*	Optional	2	Yes	No
Janitor closet	Negative	Optional	10	Yes	No
Bathroom	Negative	Optional	10	Yes	No
Personal services (barber/salon)	Negative	2	10	Yes	No

*Continuous directional control not required

high (Earnest and Loesche 1991). Lab procedures have been shown to generate dusts and aerosols containing metals. At this time, only limited information and research are available on the level, nature, or persistence of bioaerosol and particulate contamination in dental facilities.

Nitrous oxide is used as an analgesic/anesthetic gas in many facilities. The design for controlling nitrous oxide should consider that nitrous oxide (1) is heavier than air and may accumulate near the floor if air mixing is inefficient, and (2) should be exhausted directly outside. NIOSH (1996) includes recommendations for the ventilation/exhaust system.

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CHAPTER 8

JUSTICE FACILITIES

TECHNICAL and environmental factors and considerations for engineers designing HVAC systems that serve justice facilities are presented in this chapter. Most of the information presented is for facilities in the United States; regulations in other parts of the world differ significantly, and the authorities governing these facilities should be consulted directly. Refer to the 2004 *ASHRAE Handbook—HVAC Systems and Equipment* for further information on HVAC systems and equipment mentioned herein, and to other chapters of this volume for various space applications and design considerations.

TERMINOLOGY

The following terms are used throughout this chapter:

Justice Facility. Any building designated for purposes of detention, law enforcement, or rendering a legal judgment.

Cell. A room for confining one or more persons; it may contain a bed for each occupant and a toilet and wash basin.

Holding Cell. A room designed to confine a person for a short period of time; it may or may not contain a bed.

Small Jail. A facility consisting of up to 100 rooms and ancillary areas, designed for confining people.

Large Jail. A facility consisting of more than 100 rooms and ancillary areas, designed for confining people.

Prison. A facility consisting of one or several buildings and ancillary areas surrounded by high walls and/or fences, designed to confine a minimum of 500 people.

Minimum Security. A facility or area within a jail or prison that allows confined people to mix together with little supervision for periods of time during the day.

Medium Security. A facility or area within a jail or prison that allows confined people to mix together with some or total supervision for periods of time during the day.

Maximum Security. A facility or an area within a jail or prison that confines people to their cells with total supervision.

Work Release. A program that allows minimum security occupants freedom during the day to work outside the facility, but requires them to return for the night.

Courthouse. A facility consisting of courtrooms, judges chambers/offices, jury rooms, jury assembly rooms, attorney interview rooms, libraries, holding cells, and other support areas.

Police Stations. Facilities housing the various functions of local police departments. They may contain holding cells, evidence storage rooms, weapons storage, locker rooms, offices, conference rooms, interview rooms, and parking garages.

Juvenile Facilities. Also known as **family court** facilities, these facilities are for young offenders. Usually kept separate from adult facilities, they house their own court or hearing rooms, judges chambers, offices for social workers and parole officers, conference rooms, waiting areas, classrooms, sleeping rooms, intake areas, libraries, exercise rooms/areas, kitchens, dining areas, and laundry.

Inmate. A person confined to a cell, jail, prison, or juvenile facility.

Correctional Officer. A trained law officer who supervises inmates.

Correctional Officer Facilities. Areas designated for use only by correctional officers, including control rooms, break rooms, locker rooms, and storage rooms.

Inmate Areas. Areas that inmates have access to, with or without supervision, including cells, day rooms, exercise areas, outside areas, and certain ancillary areas.

Day Rooms. A room where confined people can congregate for periods of time outside of their cells during the day under supervision. The room usually contains chairs, tables, TVs, and reading and game materials.

Exercise Areas. Gymnasiums or rooms used for exercise by staff members, and areas designated for use by inmates where they can mix and exercise for short time periods during the day. This inmate area is usually outdoors or has at least one wall or the roof exposed to the outdoors.

Ancillary Areas. Support areas, including offices, kitchens, laundry, mechanical rooms/plants, electrical rooms/plants, libraries, classrooms, and rooms for exercise, health care, visitation, interviews, records, evidence, storage, fingerprinting, lineups, inmate intake, etc.

Control Room. A room that allows viewing or monitoring of various areas of the facility and/or houses electronic or pneumatic controls for door locks, lights, and other functions.

Sally Port. A room or space that encloses occupants or vehicles and allows only one door at a time to open.

Forensic Lab. Laboratory where human remains and physical evidence are examined and tested to determine whether a crime has been committed, and to identify bodies and people.

GENERAL SYSTEM REQUIREMENTS

Outside Air. All areas require outside air for ventilation to provide good air quality, makeup air for exhaust systems, and to control pressures within facilities. Minimum outside air requirements for various areas in justice (correctional) facilities can be found in publications of the American Correctional Association (ACA) and in ASHRAE *Standard* 62.1.

Equipment Locations. Access to mechanical equipment and controls must be kept secure from inmates at all times. Equipment rooms should also be located where inmates do not have access to them. Where inmates do have access, security ceilings with lockable access panels must be used when mechanical equipment and components must be located in ceiling plenums. Equipment serving areas not accessible to inmates can be located as in other facilities, unless the owner has other specific requirements. Equipment near noise-sensitive areas (e.g., courtrooms, jury rooms, attorney interview rooms) should be isolated with vibration isolators and have sound attenuation devices on supply, return, and exhaust ducts;

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penetrations for ducts and pipes to those areas and out of mechanical areas should be sealed for sound as well as fire protection.

Barrier Bars. Where ducts or openings pass into or out of secure areas, and at exterior intakes and exhausts, barrier bars are usually installed in ducts or openings that are at least 4 in. high and 6 in. wide. Barrier bars are solid steel bars mounted in a heavy-gage steel frame to match the duct or opening size. They must be installed as an assembly within a structural wall compartment whenever possible, much like a fire damper. Barrier locations should be coordinated with the facility's owner. Include the bars in static pressure calculations for airflow systems.

Air Devices. Grilles and registers are usually security-type devices constructed of heavy-gage steel and welded or built in place within the walls or ceilings of secure areas accessible to inmates, and are designed to reduce entry of obstacles into the grilles. Locations of these devices in secure areas should be coordinated with the facility's owner. Air devices serving areas not accessible to inmates may be standard grilles, registers, and diffusers. Standard diffusers may also be installed in secure areas with ceilings over 15 ft above the floor.

Outside Air Intakes and Exhausts. Louvers and grilles associated with intake and exhaust air should be located at or above the roof level, and/or (1) where inmates do not have access to them and (2) where substances cannot be discharged into them to cause harm or disruption to services and personnel within the facility. Barrier bars are usually installed at these devices.

Filtration and Ultraviolet (UV) Lights. Most areas in justice facilities use pleated throwaway filters with a minimum efficiency reporting value (MERV; see ASHRAE *Standard* 52.2) of at least 8. Higher-efficiency filters, such as HEPA or MERV 14 filters, may be required for clinic areas and isolation cells, and UV lights may also be installed to reduce bacteria and the spread of disease. Grease filters must be installed in kitchen exhaust hoods over cooking surfaces. In lieu of bringing in large amounts of outdoor air into the facility, normal outdoor air quantities may be used by installing gas-phase or carbon filters in recirculated air streams. Discuss filter applications with the owner and authorities having jurisdiction. For more information on filters, see Chapter 24 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*.

Energy Considerations

Some areas of justice facilities (e.g., cells, day rooms) are occupied 24 h/day year-round and require a large amount of outside air that is subsequently exhausted. Methods to recover exhausted tempered air and reduce the energy needed to cool and heat the outside intake air include the following:

- Sensible and enthalpy heat recovery wheels or heat exchangers may be used wherever possible.
- Runaround heat recovery coil loops may be used when exhaust and supply airstreams are separated.
- Thermal storage is available for heating and cooling.
- Variable-speed drives may be used on cooling towers, fans, pumps, supply and exhaust fans, and chillers.
- Variable-air-volume systems may be used in office spaces and other areas not requiring constant airflows.
- Supply temperature reset based on outside air temperatures may be used on heating and cooling systems.
- Economizer cycles may be used when outside air temperature and humidity meet indoor condition requirements.
- Heat captured from boiler stacks can preheat combustion air or makeup water.
- Free cooling heat exchangers provide cooling water by using cooling towers in lieu of the chiller when outside air conditions allow.
- Where reheat is required, water rejected from mechanical cooling or recaptured heat sources (e.g., from laundries) may offer economical paybacks.

- Smaller local systems may be installed to serve areas that are occupied at all times or operate seasonally, so that larger equipment may be shut off at certain times. Modular systems allow various modules to be staged on and off as needed to serve the same purpose.
- Night and holiday setback temperatures at least 5°F above or below the normal occupied settings, with morning warm-up or cooldown, should be used wherever possible for areas that are not always occupied or have varying occupancies.
- Evaporative cooling systems may be used in arid climates to replace water chillers and/or cooling towers. They may also be used in other regions to provide makeup air for some facilities, such as kitchens and laundries.
- Heat pumps may be used wherever possible. See Chapter 8 in the 2004 *ASHRAE Handbook—HVAC Systems and Equipment* for a discussion of these systems.
- Combined heat and power (CHP) systems may be used in larger facilities. See Chapter 7 in the 2004 *ASHRAE Handbook—HVAC Systems and Equipment* for a discussion of these systems.

Whatever form of energy recovery is used, all systems should be examined for the rates of return on the cost of implementing and operating the systems.

Heating and Cooling Plants and Mechanical Rooms

Most larger justice facilities have central heating and cooling plants, with mechanical rooms located throughout the facility. Smaller facilities generally use local systems, with mechanical rooms located throughout the facility or with a combination of rooftop units or split systems. For larger facilities, central plants with water chillers, cooling towers, and fuel- or dual-fuel-fired steam or hot-water boilers are normally used to serve air-handling units, fan-coil units, reheat coils, and other equipment in mechanical rooms throughout the complex. Primary/secondary or variable-speed pumping of hydronic systems should also be considered.

The heating and cooling requirements are for continuous operation while there are occupants. Essential equipment should be backed up with standby units for use during maintenance or equipment failure. In addition, major components may need to be braced for seismic and/or wind restraint to ensure continuous service. For seismic design, all justice facilities should be considered essential facilities; see Chapter 54 for details. Zoning of various areas for occupancy times and seasonal changes should be factored into system arrangements and types.

Plants and mechanical rooms should be located in areas not accessible to inmates, unless supervised maintenance and/or operation is performed by inmates. For central plants serving very large facilities, the plant may be located away from the complex (outside the fences or walls). Some of these plants use distribution tunnels from the plant to the various buildings in lieu of direct burial of the piping. Access to these tunnels must be kept secure from inmates. Vertical duct and pipe chases in facilities are usually located adjacent to cell areas, incorporated within plumbing chases, and stacked to connect to the heating, cooling, and ventilating or exhaust equipment. Service to these chases must be from outside the cell areas.

The capabilities of maintenance personnel and the training to be provided them should be considered in selecting the types of system and equipment to be used in the design. The owner and/or maintenance personnel should be consulted to determine the best combination of components, systems, and location of the plants and mechanical rooms for the facility.

Mechanical equipment within central plants and mechanical rooms must have the proper vibration isolation, flexible pipe and duct connections, and duct-mounted sound attenuators (where needed) to prevent transmission of vibration and noise to sensitive spaces. Mechanical rooms may have to be sound-treated with acoustical materials to prevent room noise from being transmitted to

adjacent spaces. Equipment types may also have to be considered for noise transmission, such as fan types. See Chapter 47 for vibration and noise applications.

Controls

Controls serving HVAC systems for small facilities can be local and consist of electric, electronic, pneumatic, or a combination of all of these, and may need to be located in lockable control boxes. Controls for larger facilities are usually electronic or a combination of electronic/electric and pneumatic, and are connected to a central, computerized system or building automation system (BAS) so that operators can remotely manage and monitor systems more efficiently. Thermostats and other sensors in or near inmate areas should be inaccessible to inmates (e.g., located in return or exhaust ducts). Control panels should be locked and located within secure areas. All interconnecting wiring and pneumatic tubing should be concealed from inmates and kept secure.

Fire/Smoke Management

All confined occupants of justice facilities need to be kept safe from fire and smoke. Early detection of fires should be considered in all facilities. Installation of fire and smoke detectors should be discussed with the owner. These detectors need to be installed in secure areas or within the units and not be accessible to inmates.

Smoke control systems should also be considered to facilitate evacuation of inmates to safe areas during an emergency, especially if the facility has no other means to evacuate the inmates to secure areas outside the buildings. The owner should be aware of the costs and complexity of smoke management before implementation. See Chapter 52 for information on fire and smoke management.

Health Issues

Some areas within large facilities, and some cells within small facilities, should be designed to provide negative pressures within them to provide isolation from other spaces for inmates with communicable diseases such as tuberculosis (TB). These spaces should have separate, dedicated exhaust systems, alarms, and controls. Application and component requirements should be discussed with the owner. See Chapter 7 for discussions of health care systems and applications.

JAILS, PRISONS, AND FAMILY COURTS

Jails may be a stand-alone structure or part of a larger facility that will confine inmates. Some are totally self-supported and have their own kitchen, laundry, intake room, fingerprinting, storage for personal belongings, sally ports, parking garage, central plants, and other support areas. Security may be anything from minimum to maximum, and may include a work release area, as well. Jails may be located within the city limits or outside of the city.

Prisons are large facilities that confine inmates for longer periods of time than jails, and may have all levels of security and fences or walls with guard towers. Prisons are usually totally self-supported and have every facility required to serve its needs in one large or several small buildings, including laundries, kitchens, dining halls, library, gyms, auditoriums, cell blocks, health clinics, offices, interview rooms, visiting areas, storage rooms for personal belongings, sally ports, intake and release areas, isolation cells or areas, central heating and cooling plants, and correctional officer facilities. Prisons are generally located outside of cities and towns.

Family courts or **juvenile detention centers** are similar to jails but house young offenders up to the age of 18. These facilities include courtrooms, judges' chambers and offices, interview rooms, exercise areas, lockable sleeping areas, classrooms, offices for social workers, kitchens, laundries, and other support facilities. Generally, offices, courtrooms, judges' chambers, interview rooms,

exercise areas, classrooms, kitchens, and laundry are unoccupied after working hours, so the mechanical systems for these facilities must be able to respond to various occupied hours of operation.

HVAC Design Criteria

- Use outdoor **summer temperature conditions** equal to ASHRAE 1% design dry bulb and mean coincident wet bulb. For outdoor **winter temperature conditions**, use ASHRAE 99% design dry bulb and mean coincident wet bulb.
- **Indoor air** should be at 74°F and 50% rh for summer conditions and occupancy, and 72°F and 20 to 35% rh for winter, unless otherwise noted.
- For **cells** or **sleeping room** noise levels, use a maximum of 70 dBA (day) and 45 dBA (night), with minimum constant-volume airflows in accordance with ASHRAE *Standard* 62.1. Maintain negative room pressure, especially when the room or cell contains a toilet.
- For **classrooms**, use noise levels between 25 and 30 RC, and airflows in accordance with ASHRAE *Standard* 62.1. See Chapter 6 for discussion of educational facilities.
- **Interview rooms** should have the same noise levels as for classrooms, with minimum airflows of 6 air changes per hour (ach) of supply air with a minimum of 0.06 cfm/ft^2 of outdoor air through low-noise diffusers and grilles.
- When **guard stations** are separate rooms for observing inmates, minimum airflow must be in accordance with ASHRAE *Standard* 62.1. Airflows should be constant volume, and noise levels should be 35 to 45 RC. This room may be occupied 24 h a day.
- **Control rooms** should be treated as guard stations. Room loads include computer equipment and video monitors, where required. This room is occupied 24 h a day.
- **Laundries** are usually heated in winter when not used, and well ventilated to remove generated heat but not air conditioned when in use. All air supplied should be exhausted and the room kept at a negative pressure during operating hours. Maximum noise levels are about 45 to 50 RC. Energy conservation measures may include evaporative cooling if tempered air is supplied to the space; discharged warm laundry water may be recovered for preheating makeup water. See ASHRAE *Standard* 62.1 for minimum airflow requirements.
- **Libraries** require close space temperature and humidity control, with 75°F db year-round and 40% (winter) to 50% (summer) humidity. Constant-volume airflow meeting ASHRAE *Standard* 62.1 is required. See Chapter 21 for details on libraries.

System Requirements

HVAC equipment is generally either a constant- or variable-air-volume (VAV) system. Constant-volume systems are usually used in dayrooms, cells or sleeping quarters, and storage areas. Variable-volume systems may be used in administrative offices, interview rooms, and visitor areas. Cells and sleeping areas are usually exhausted to help control odors. Intake rooms are also exhausted, with supply and exhaust air outlets located high and low to sweep the room and help control odors. Systems must be able to adjust to variable loads and occupancy times, and be zoned to meet the requirements of ASHRAE *Standard* 62.1. Back-up equipment should be provided that serve dayrooms, cells, and critical spaces.

Mechanical equipment must be located outside of areas occupied by inmates, but must be accessible for maintenance. Cells, sleeping quarters, and dayrooms are usually provided with security-type grilles for supply, return, or exhaust.

Jails, family courts, and prisons located within city limits or near neighborhoods need to be concerned about noise from mechanical equipment and inmates transmitted to the outdoors. Louvers for equipment, indoor exercise rooms, or windows where inmates congregate need noise abatement. Equipment needs to be examined not only for noise transmitting into the facility but transmitted to the

outdoors. See Chapter 47 for information on noise and vibration control.

Dining Halls

Dining halls are usually located in large facilities. Space loads vary, depending on occupancy schedules for food preparation and eating. Food-warming station loads also need to be included in the space loads. Smaller facilities use a central kitchen to prepare the food, which is then delivered to inmates on trays in warming carts and may then be reheated in ovens just before serving. If ovens are used, they must be included in the local space loads. Latent loads for eating must also be allowed for.

Kitchens

Kitchens are either centrally located and the prepared food is then transferred to the inmates, or they are associated with the dining halls. Kitchens are full service and include pantry, freezers, coolers, ovens, stoves, kettles, fryers, grilles, dishwashers, and exhaust hoods. In many justice facilities, inmates prepare food, so the kitchen should be designed as a secure area. See Chapter 31 and ASHRAE *Standard* 154 for information and requirements on kitchen ventilation.

Guard Stations

Guard stations either are located within the cell and dayroom area, where guards mingle with inmates, or they are remote and enclosed, where guards can observe cells and dayrooms through secure glass windows. Guard stations are staffed while inmates are awake and not in their cells, and may also be staffed during the night if the owner requires it.

Control Rooms

Control rooms use cameras to remotely monitor inmates, and control doors into and around inmate and other secure areas. These rooms are occupied at all times; room loads should include the control panels and video monitors.

Laundries

Laundries are usually located in their own building or separate rooms and contain washing machines, dryers, and pressing machines. The laundries are very warm places and may be tempered with evaporative cooling and outdoor air economizer cycles with full room exhaust. Spot cooling is recommended for personnel at work stations. Warm water discharged from the washing machines may be recovered through special laundry heat exchangers to preheat the makeup water. Laundries usually have steam supplied from the central plant or their own boilers for heating the wash and rinse water and the pressing machines. If inmates work in laundry service, the space should be designed as a secure area.

COURTHOUSES

This section covers courtrooms in civil, bankruptcy, and criminal courthouses, as well as support divisions for judges' chambers, clerk of court, jury rooms, library, fitness center, marshal areas, jail cells, and administrative areas. Courtrooms generally do not have a clear schedule of operation; however, they generally operate between 9:00 AM until approximately noon. Support staff generally work between 8:00 AM and 5:00 PM, except in constant-occupancy spaces such as marshal areas, jail cells, and other administration areas. Jury areas are generally 9:00 AM to 5:00 PM, but may be occupied much longer, depending on the type of trial.

Courthouses (state, federal, and county) should be designed to suit operational hours and fluctuating visitors and staff occupancies for maximum energy conservation and optimum controls. Architectural features in courtrooms are generally above standard

conventional design, and often include wood and ornate ceilings, which require both temperature and humidity control.

HVAC Design Criteria

- Use outdoor **summer temperature conditions** equal to ASHRAE 1% design dry bulb and mean coincident wet bulb. For outdoor **winter temperature conditions**, use ASHRAE 99% design dry bulb and mean coincident wet bulb.
- **Indoor air** should be at 74°F and 50% rh for summer conditions and occupancy, and 72°F and 20 to 35% rh for winter.
- If provided, the **smoke purge system** in the courtroom should be activated manually as well as automatically.
- All **openings** carrying piping through the slab or through partitions must be sealed with appropriate fire/smoke-resistive material. All air ducts leading to and from sensitive spaces must be acoustically treated with 2 in. thick, 3 lb/ft^2 density duct lining for at least 12 ft from the supply diffusers or return air intake.
- Design HVAC systems for **optimum flexibility in scheduling** use of courtrooms, chambers, and jury areas.
- All **fresh and exhaust air locations** should be at least 40 ft above grade, or as high as possible to protect against terrorist attack (see Chapter 58 for more information).

System Requirements

HVAC equipment is generally either constant- or variable-volume air systems. The same independent system should be used for courtrooms, judges' chambers, and jury suites. Every courtroom should have an independent system that can maintain the required temperature and humidity set points in the space, using a thermostat and a humidistat designed to precool before scheduled occupancy. Controls for jury deliberation rooms and judges' chambers should be placed in the conditioned space and be adjustable for variable occupancy.

HVAC systems for courthouses should be zoned to meet fresh-air requirements of ASHRAE *Standard* 62.1. Central plant systems (including chillers, boilers, and air-handling units) should be designed for 24 h operation, intermittent occupancy, and after-hours activity. All VAV terminal units and reheat coils should be located outside courtrooms and deliberation rooms, and should be accessible for maintenance.

Courtrooms/Chambers

The HVAC system serving judges' chambers, courtrooms, and trial jury suites should provide an average occupied temperature of 74°F. The courtroom system zone should allow temperature sensors to be reset from the building automation system to precool to 70°F before scheduled occupancy. Humidity sensors should maintain minimum relative humidity at 20% (winter) to 50% rh (summer).

Provide a minimum of 6 ach for rooms with ceiling heights up to 15 ft, and 8 ach for rooms with higher ceilings. Systems should be designed to meet these requirements when spaces are fully occupied. These airflows should be reduced during long unoccupied hours, at night, and on weekends and holidays.

Each courtroom should be served by a dedicated fan system, and return air from each courtroom and associated areas (jury rooms, judge's chambers, etc.) must be ducted directly back to the unit or system.

Jury Facilities

Trial jury suites should be served from the same system as the associated courtrooms. (A separate temperature and humidity control for each trial jury room is desirable.)

Air distribution systems must provide separate temperature control and a high degree of acoustical isolation, particularly in grand jury and trial jury rooms. Return air must be ducted directly back to the unit or exhaust air riser. Ductwork must be treated to meet the acoustical deliberation room design criterion of a maximum of 25 to

35 RC. Before recommending underfloor air distribution, filtration, temperature, distribution, air balancing, and commissioning method should be considered.

In the jury assembly room, deliberation room, and associated toilet rooms, the system must provide 10 ach with 80 to 85% return and exhaust.

Libraries

See the discussion on libraries in the section on Jails, Prisons, and Family Courts.

Jail Cells and U.S. Marshal Spaces (24-h Spaces)

A separate air-handling system tied to the main HVAC system should be able to operate independently after hours. A separate 100% fresh and exhaust air system should be provided to jail cells; it should have security grilles and barrier bars, and negative pressure should be maintained.

Marshal spaces should be treated as normal office areas, except for cell areas and exercise rooms. Contents usually include computer and radio equipment, cells, exercise rooms, gun vaults, and perhaps sleeping rooms, and may be occupied 24 h a day. HVAC systems serving these areas should be separate from other systems.

Fitness Facilities

These facilities should be tied to the 24 h system and have a separate 100% fresh air unit able to dehumidify air to 50°F dp. Exhaust air and heat recovery systems should be provided, and the space should be maintained under negative pressure. See Chapter 4 for more information on Gymnasiums.

Acoustic Performance

Acoustic performance should be a major consideration when selecting HVAC equipment. Systems serving courtrooms and auxiliary spaces should be designed with sound attenuation to provide consistent and acceptable sound levels (25 to 40 RC). This is particularly critical in court facilities that require extensive use of sound and audio/visual (A/V) equipment for recording and presentations. Vibration and acoustic performance should be in accordance with guidance in Chapter 47.

To control noise during all modes of operation and for all load conditions, HVAC systems should be provided with one or more of the following:

- Sound traps and acoustic lining in supply and return or exhaust ductwork
- Low-velocity, low-static-pressure fan systems (pay special attention to fan types for noise levels)
- Special low-noise diffusers

Return air should be ducted, especially in courtrooms and jury rooms. Special attention should be given to location of any partitions extending to the floor above and the acoustical treatment around the penetrations of these partitions.

HVAC equipment, including air-handling units (AHUs) and VAV boxes, should not be located close to courtrooms, jury rooms, and chambers. The minimum distance should be 25 ft between the space and these units. General system design needs to provide appropriate treatment of mechanical supply/return ducts to minimize sound and voice transmission to surrounding areas.

Room criterion (RC) defines the limits that the octave-band spectrum of noise sources must not exceed; for court and jury facilities, it should range from 25 to 40. For sound level maintenance, the courtroom should be served by constant-volume air supply. The system must also support variable outside air requirements and variable cooling loads. Air ducts serving trial and grand jury suites must be lined with 2 in. thick, 3 lb/ft^2 density acoustical absorption material for at least 12 ft from the diffuser or return air intake.

FORENSIC LABS

In forensic labs, physical evidence is examined, autopsies may be performed, human remains are tested and identified, firearms are tested, evidence is stored, all aspects of suspected criminal activity are reviewed to determine whether a crime has been committed, and people are identified from evidence taken at crime scenes.

The labs contain many chemicals, fume hoods, ovens, centrifuges, microscopes, x-ray units, and other laboratory equipment that need to be considered in space loads and ventilation requirements. Some lab equipment is sensitive to changes in temperature and humidity. See Chapter 14 for more information on laboratories.

Forensic labs may be stand-alone facilities, part of other facilities, or specific departments may be separated and located in other facilities. Components may include offices, data rooms, storage rooms, laboratories, autopsy rooms, interview rooms, inspectors offices, mechanical and electrical rooms or central plants, firearms rooms, x-ray rooms, photo developing rooms, and body or evidence drying rooms.

HVAC Design Criteria

- Use outdoor **summer temperature conditions** equal to ASHRAE 1% design db and mean coincident wb. For outdoor **winter temperature conditions**, use ASHRAE 99% design dry bulb and mean coincident wet bulb.
- For **indoor air**, 74°F and 50% rh for summer conditions and occupancy, and 72°F and 20 to 35% rh for winter, depending on user requirements.
- **Autopsy rooms** may require room temperatures as low as 60°F and airflows as high as 15 ach when the medical examiners are suited in heavy or rubber garments during an autopsy, or when odors are especially noticeable. Autopsy rooms must be kept under negative pressure, and air should be exhausted high and low in the space. Specific autopsy sinks may include their own exhaust grilles and need to be exhausted when they are in use. All outdoor air may be required for odor control. Noise levels of 20 to 35 RC may be required, because of recordings made during autopsies.
- **Laboratories** should be kept at 70 to 72°F and at least 20 to 30% rh in winter, and 70 to 74°F and 50% rh in summer. These rooms often contain fume hoods and the supply, room exhaust, and hood exhaust airflows must all be controlled together to keep the space under a negative pressure, although some laboratory operations may require positive pressure. All room air must be exhausted and not recirculated. These spaces contain large equipment loads that produce high sensible and latent heat gains at various times. Systems serving these rooms must be flexible enough to react to these load changes and maintain their room sensor set points. Most labs require year-round cooling and dehumidification with reheat to prevent build-up of excessive humidity under some weather conditions. Clean steam may be required for the fume hoods and humidifiers serving the labs; fume hoods and lab benches may also require specially treated water [e.g., deionized (DI) water], inert gases, and natural gas supplies.
- **Microscope tables** need to be isolated from vibrations from mechanical equipment and from building vibrations; information on vibration isolation can be found in Chapter 47.
- Usually, forensic labs are **occupied 24 h a day**, with a small number of rooms that may only be occupied during normal business hours; equipment should be selected, zoned, and controlled to allow for these various occupancies.

System Requirements

Offices and general storage in forensic laboratories are served by normal air-handling systems and should maintain normal room airflows and temperature and humidity set points. Return air may be recirculated. The offices should be kept at positive pressure to keep odors out and to allow use as makeup air for negative-pressure

spaces (e.g., storage areas for formaldehyde, which should be exhausted to the outdoors). Systems serving the offices may be required to have their own independent heating and cooling units or terminal units, because their occupancy schedules may differ from those of the labs and other areas.

HVAC systems in cold climates that use 100% outdoor air may experience maintenance problems with frozen hydronic coils unless glycol is used in the water system or the cooling coils are drained in the winter. If internal face-and-bypass dampers are used, cold air can become stratified and freeze portions of the coils. External or integral coil face-and-bypass dampers often are a better application, because they allow cold air to move around the coil or pass through a tempered coil, which reduces the freezing potential.

Ducted supply and exhaust air systems should be used for labs and autopsy rooms. The amount of negative pressure should be maintained carefully in these rooms, so that doors open without excessive door-opening force, as required for smoke control systems (see Chapter 52).

Variable-volume control of supply and exhaust fans may be provided with variable-frequency drives (VFDs). Control of the VFDs should allow for offset of supply and exhaust airflows and to adjust for variances within the systems, such as for dirty filters.

Fume hood exhaust fans should be located on the roof at least 25 ft from any outdoor air intakes, so they will discharge a vertical plume above and away from the roof. Exhaust fans should not be located inside the occupied space; this can produce a positive air pressure in the exhaust duct downstream of the fan, causing leakage back into the space. Consider using redundant exhaust fans or an $N + 1$ exhaust fan system for critical areas.

Exhaust duct and fan materials need to be checked for corrosion resistance against chemicals from fume hoods and laboratories. Coordinate with laboratory personnel about these fumes. Fiberglass, plastic, stainless steel, or coated galvanized duct materials should all be considered. Internal duct lining should never be used in exhaust ducts. Also, consider requiring the exhaust fan to be explosionproof and spark-resistant if materials exhausted may be explosive.

Care must be taken in locating supply air diffusers in relation to the fume hoods, so that exhaust air flowing into the fume hood is not disturbed and does not create turbulence in front of the hood. Supply air should be introduced slowly in a semilaminar flow pattern away from the hoods.

Intake Air Quality

The quality of outdoor air brought into forensic laboratories should be carefully controlled. Usually, these labs are in urban environments close to traffic, parking garages, industrial areas, emergency generator exhausts, restaurant exhausts, and other contaminants. Also, risks from bioterrorism should be addressed by locating outdoor air intakes where they are inaccessible to the public (see Chapter 58). MERV 13 or 14 final filters may be required for critical lab areas, such as DNA extraction labs, autopsy rooms, and toxicology labs, to prevent cross contamination from other processes in the facility or from other outside air influences.

Firearms Laboratories

Firearms testing labs often contain microscope rooms, firearms and ammunition storage rooms, workbench tool rooms, catalog reference rooms, and researcher offices.

Ballistic shooting ranges are usually kept under negative pressures because of smoke emissions. These rooms should be treated for noise attenuation to prevent noise being transmitted to other spaces and reverberating within the room. Air should be supplied near the shooter's breathing zone and exhausted at or near the bullet trap and downstream of the muzzle of the firearm. Using two-speed supply and exhaust fans or fans with VFDs is recommended, so that fan speed is lower when no shooting is occurring. All exhaust systems should be ducted to roof-mounted fans.

Catalog reference rooms and all offices may operate at different hours than the labs, and may be served by their own HVAC systems or systems with equivalent occupancy schedules. Room temperature and pressures should be the same as for general offices, and return air can be recirculated back to the air-handling system.

Acoustic Performance

Acoustic performance should be a major consideration in selecting HVAC equipment. Systems serving laboratory and autopsy spaces should be designed with sound attenuation to provide consistent and acceptable sound levels (25 to 40 RC). This is particularly critical for autopsy rooms that require extensive use of sound and A/V equipment for recordings. Vibration and acoustic performance should be in accordance with Chapter 47.

To control noise during all modes of operation and for all load conditions, the HVAC systems should be provided with one or more of the following:

- Sound traps and acoustic lining in supply and return ductwork
- Sound trap in exhaust ductwork
- Low-velocity, low-static-pressure fan systems (pay special attention to fan types for noise levels)
- Special low-noise diffusers

Pay special attention to location of any partitions extending to the floor structure above and the acoustical treatment at penetrations of these partitions to provide sound attenuation around the perimeter of ducts and pipes to prevent noise transmissions.

Critical Spaces

Rooms containing freezers or coolers and critical computer rooms should be served by their own independent cooling systems with emergency power back-up, to ensure operation in the event of an extended power outage.

Room pressure controls and monitors should be provided in critical laboratory areas, autopsy rooms, firearms testing rooms, storage rooms that contain hazardous materials, DNA rooms, evidence vaults, trace evidence rooms, drying rooms, photo developing rooms (darkrooms), and other areas deemed necessary by the owner. Room pressures should be continually maintained by measuring supply and exhaust airflows to the room and varying the supply air rate to maintain a differential from the exhaust airflow rate.

Evidence Vaults. Humidity control and cross contamination prevention are critical, as is exhausting odors from drugs stored in the vault. The room must be kept under negative pressure at 72 to 74°F and 30% rh in the winter and no more than 50% rh in the summer. Barrier bars must be installed on any duct penetrations for these rooms. Firestopping and combination smoke/fire dampers should be installed at duct penetrations.

Photo Developing. Photographic darkrooms must be kept under negative pressure and exhausted to the outdoors, because of the chemicals stored and used within the room. Exhaust should be located behind developing sinks and counters. Outdoor air should be supplied at a minimum of 0.5 cfm/ft², from low-velocity diffusers behind lab personnel. Exhaust ducts and fans must be corrosion-resistant and contain combination fire/smoke dampers and firestopping at the penetrations. Exhaust fans should also be explosionproof and spark-resistant. See Chapter 20 for information on temperatures and humidity levels.

Photo Studios. Photo studios have high heat loads because of their excessive lighting requirements. Systems serving these spaces should be designed to minimize noise and air motion and handle variable loads, because of the occupancy schedule and lighting levels.

Trace Rooms. Trace rooms are laboratories where very small amounts of evidence are examined and tested. Consequently, supply airflows need to be low, laminar flow away from the work surfaces to prevent any disturbance of materials. These rooms should be

treated as any other lab for temperature, humidity, pressurization, and airflows.

Drying Rooms. Some forensic labs have rooms where evidence must be dried very slowly, to preserve it. HVAC systems serving these rooms should be separate from other systems to prevent cross contamination; temperatures should be maintained between 75 and 80°F, pressure should be negative, and all air exhausted to the outdoors. Laminar air supply should be introduced into the room and high and low exhaust inlets should be installed. Supply air should receive final HEPA filtration.

Laboratory Information Management Systems (LIMS)

Many labs use a separate laboratory information management system to document temperature, pressure, and humidity levels in critical laboratory spaces for validation and certification purposes. System requirements need to be coordinated with the owner.

Historical data storage and retrieval of selected processes and system events, system documentation, and data should be required. This function should allow report formatting and generation from archived historical data. Typical reports consist of alarm summaries, limit summaries, report time reports, all-points logs, trend listing, time of day start/stop schedules, message summaries, energy logs, and maintenance reports.

An independent commissioning agent should be retained at the beginning of system design and should perform complete, detailed commissioning services, including system start-up services, operation and maintenance training and documentation, control of shop drawings, and operation and maintenance manuals. A validation procedure may also be required to ensure the system's operational effectiveness meets both the design intent and operator's requirements.

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CHAPTER 9

AUTOMOBILES AND MASS TRANSIT

AUTOMOBILES

THERMAL systems in automobiles (HVAC, engine cooling, transmission, power steering) have significant energy requirements that can adversely affect vehicle performance. New and innovative approaches are required to provide the customer the desired comfort in an energy-efficient way. In recent years, efficiency of the thermal systems has increased significantly compared to systems used in the early to mid-1990s. Providing thermal comfort in an energy-efficient way has challenged the automotive industry to search for innovative approaches to thermal management. Hence, managing flows of heat, refrigerant, coolant, oil, and air is extremely important because it directly affects system performance under the full range of operating conditions. This creates significant engineering challenges in cabin and under-hood thermal management. Optimization of the components and the system is required to fully understand the components' effects on the system. Thus, modeling the components and the system is essential for performance predictions. Simulation of thermal systems is becoming an essential tool in development phase of projects. Durability and reliability are also important factors in design of these systems.

Environmental control in modern automobiles usually consists of one (or two for large cars, trucks, and sport utility vehicles) in-cabin air-handling unit that performs the following functions: (1) heating, (2) defrosting, (3) ventilation, and (4) cooling and dehumidifying (air conditioning). This unit is accompanied by an under-hood vapor cycle compressor, condenser, and expansion device. The basic system can be divided into three subsystems: air handling, heating, and refrigeration (cooling). All passenger cars sold in the United States must meet defroster requirements of the U.S. Department of Transportation (DOT) Federal Motor Vehicle Safety *Standard* 103 (FMVSS), so ventilation systems and heaters are included in the basic vehicle design. The most common system today integrates the defroster, heater, and ventilation system. In the United States, the vast majority of vehicles sold today are equipped with air conditioning as original equipment.

DESIGN FACTORS

General considerations for design include cabin indoor air quality (IAQ) and thermal comfort, ambient temperatures and humidity, operational environment of components, airborne contaminants, vehicle and engine concessions, physical parameters, durability, electrical power consumption, cooling capacity, occupants, infiltration, insulation, solar effect, vehicle usage profile, noise, and vibration, as described in the following sections.

Thermal Comfort and Indoor Air Quality (IAQ)

ASHRAE *Standard* 55 provides information on the airflow velocities and relative humidity required to provide thermal comfort. Effective comfort cooling system design in cars must create air movement in the vehicle, to remove heat and occupants' body effluents and to control moisture build-up. Assuming an effective temperature of 71°F with no solar load at 75°F, 98% of people are comfortable with zero air velocity over their body. If the temperature increases to 81°F, the same number of people are comfortable with an air velocity of 500 fpm. If panel vent outlets can deliver sufficient air velocity to the occupants, comfort can be reached at a higher in-vehicle temperature than with low airflow (Figure 1).

Several modeling manikins for predicting human physiological behavior are described in Guan et al. (2003a, 2003b, 2003c), Jones (2002a, 2002b), and Rough et al. (2005).

During the increasingly common gridlock or stop-and-go conditions, **tailpipe emissions** can make outside air (OA) extremely polluted, and it is important to ensure that passengers' exposures to these gases do not exceed ACGIH (2007) short- or long-term exposure limits.

Tailpipe emissions include

- Nitrogen oxides (NO_x), which include both nitric oxide (NO) and nitrogen dioxide (NO_2), which always occur together (Pearson 2001)
- Carbon monoxide (CO), which forms in the combustion chamber when oxygen supply is insufficient
- Hydrocarbons (HCs)
- Volatile organic compounds (VOCs)

Diesel engines emit mainly NO_x and HC, and gasoline engines emit mainly CO and HC. Worldwide, road transportation accounts for approximately 50% of NO_x emissions, and gasoline-powered
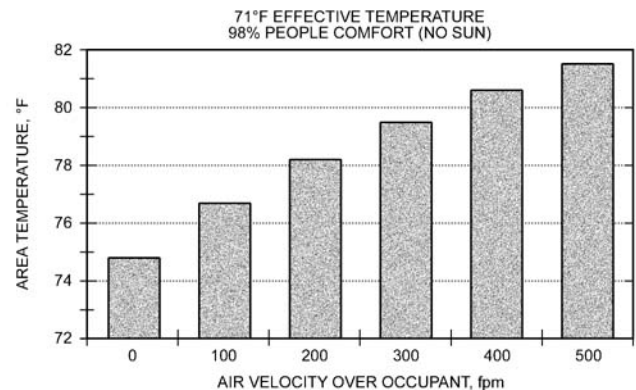
Fig. 1   Comfort as Function of Air Velocity
(Atkinson 2000)

The preparation of this chapter is assigned to TC 9.3, Transportation Air Conditioning.

vehicles alone account for 32% of HC emissions in the United States.

To limit passengers' exposure to tailpipe emissions, the blower unit's air intake door can be switched from outside air mode to recirculation mode during times of traffic congestion and likely poor OA quality (Mathur 2006).

Carbon dioxide (CO$_2$) from passengers' exhalations can also build up in the cabin, especially in low-body-leakage vehicles, so recirculation mode should not be used for extended periods. A recommended strategy is to limit recirculation to a relatively short period (e.g., 30 min), after which the system switches to OA. A CO$_2$ sensor can be installed to monitor levels in the cabin, and automatically switch to OA mode when set levels are exceeded.

Relative humidity also affects cabin IAQ. Too high a level affects occupant comfort and can lead to condensation and fogging on windows. A relative humidity sensor can detect excessive humidity and intervene.

See the section on Controls for more information on cabin IAQ.

Cooling Load Factors

Occupancy. Occupancy per unit volume is high in automotive applications. The air conditioner (and auxiliary evaporators and systems) must be matched to the intended vehicle occupancy.

Infiltration. Like buildings, automobiles are not completely sealed: wiring harnesses, fasteners, and many other items must penetrate the cabin. Infiltration varies with relative wind/vehicle velocity. Unlike buildings, automobiles are intended to create a relative wind speed, and engines may emit gases other than air. Body sealing and body relief vents (also known as the drafter) are part of air-conditioning design for automobiles. Occasionally, sealing beyond that required for dust, noise, and draft control is required.

By design, vehicles are allowed to have controlled body leakage that allows air movement in the vehicle to provide comfort to the passengers. This also helps control moisture build-up and the occupants' perceived comfort level. However, excessive body leakage results in loss of heating and cooling performance. Vehicle body leakage characteristics typically are significantly different in dynamic conditions in comparison to the static conditions. Air can leak from the vehicle's doors, windows, door handles, and trunk seals (uncontrolled exit points); drafters allow a controlled exit for air from the cabin, and should be self-closing to prevent inflow when the body pressure is negative with respect to the exterior pressure. According to SAE *Standard* J638, infiltration of untreated air into the passenger compartment through all controlled and uncontrolled exit points should not exceed 350 cfm at a cabin pressure of 1 in. of water (Atkinson 2000). However, each vehicle has different body leakage characteristics. Some vehicles have two drafters inside the trunk on either side, and some have only one.

Insulation. Because of cost and weight considerations, insulation is seldom added to reduce thermal load; insulation for sound control is generally considered adequate. Additional dashboard and floor thermal insulation helps reduce cooling load. Some new vehicles have insulated HVAC ducts to reduce heat gain during cooling and heat loss during heating mode. Typical interior maximum temperatures are 200°F above mufflers and catalytic converters, 120°F for other floor areas, 145°F for dash and toe board, and 110°F for sides and top.

Solar Effects. The following four solar effects add to the cooling load:

- **Vertical.** Maximum intensity occurs at or near noon. Solar heat gain through all glass surface area normal to the incident light is a substantial fraction of the cooling load.
- **Horizontal and reflected radiation.** Intensity is significantly less, but the glass area is large enough to merit consideration.

- **Surface heating.** Surface temperature is a function of the solar energy absorbed, the vehicle's interior and exterior colors, interior and ambient temperatures, and the automobile's velocity.
- **Vehicle colors and glazing.** The vehicle's interior and exterior colors, along with the window glazing surfaces (clear or tinted), strongly affect vehicle soak temperature. Breathing-level temperatures after a 1 h soak can be 40 to 60°F higher than ambient, with internal surfaces being 50 to 100°F above ambient (Atkinson 2000).

Ambient Temperatures and Humidity. Several ambient temperatures need to be considered. Heaters are evaluated for performance at temperatures from –40 to 70°F. Air-conditioning systems are evaluated from 40 to 110°F, although ambient temperatures above 125°F are occasionally encountered. The load on the air-conditioning system is also a function of ambient humidity (at most test conditions this latent load is around 30% of the total). Typical design points follow the combinations of ambient temperature and humidities of higher probability, starting at around 90% rh at 90°F and with decreasing humidity as temperature increases.

Because the system is an integral part of the vehicle, the effects of vehicle-generated local heating must be considered. For interior components, the design high temperature is usually encountered during unoccupied times when the vehicle is soaked in the sun. Interior temperatures as high as 190°F are regularly recorded after soaks in the desert southwestern United States. Achieving a comfortable interior temperature after such a hot soak is usually one of the design conditions for most vehicle manufacturers.

Operational Environment of Components

Underhood components may be exposed to very severe environments. Typical maximum temperatures can reach 250°F. The drive to achieve more fuel-efficient automobiles has reduced available space under the vehicle hood to a minimum. This crowding exposes many components to temperatures approaching that of exhaust system components. Heat from the vehicle also adds to the cooling loads that the air-conditioning system must handle. During idle, heat convected off the hood can raise the temperature of the air entering the air inlet plenum by as much as 10 to 25°F (Mathur 2005a). A similar effect is found during idle when air from the engine compartment is reentrained into the air flowing through the condenser (Mathur 2005b). Air temperatures as high as 160°F have been encountered on parts of a vehicle's condenser during operation with a tail wind in ambient temperatures as low as 100°F. Typically, front air management is improved by using air guides and seals to prevent air bypassing either the condenser or radiator at idle. Significant improvements in vent outlet temperatures (a maximum of 7°F) and cabin temperatures (2 to 6°F) and a reduction in head pressures (30 to 77 psi) have been obtained. Recirculation of hot engine compartment air was reduced from 52.2°F over ambient (base case) to approximately 27°F over ambient. Further details are provided in the section on Vehicle Front-End Design.

Airborne Contaminants and Ventilation

Normal airborne contaminants may include bacteria, pollutants, vapors from vehicle fluids, and corrosive agents (Mathur 2006). Exposure to these must also be considered when selecting materials for seals and heat exchangers. Incorporating particulate and/or carbon filters to enhance interior air quality (IAQ) is becoming common. Air-handling systems in virtually all vehicles are capable of exceeding the ventilation recommendations for buildings and public transportation in ASHRAE *Standard* 62.1. However, the driver has complete control of the HVAC system in the vehicle, and can reduce cabin airflow to virtually zero when desired (e.g., before warm-up on cold days).

Power Consumption and Availability

Many aspects of vehicle performance have a significant effect on vehicular HVAC systems. Modern vehicles have a huge variety of electric-powered systems. The need to power these systems while maintaining fuel efficiency leads manufacturers to demand a high level of efficiency in electrical power usage. On some vehicles, electrical power use is monitored and reduced during times of minimal availability. The mass of the HVAC system is also closely controlled to maintain fuel efficiency and ride or handling characteristics. The power source for the compressor is the vehicle's engine. At engagement, the need to accelerate the rotational mass as well as pump the refrigerant can double the engine torque. This sudden surge must not be perceptible to the driver, and is controlled through careful calibration of the engine controls. Automotive compressors must provide the required cooling while compressor speed varies with the vehicle condition rather than the load requirements. Vehicle engine speeds can vary from 500 to 8000 rpm.

Physical Parameters, Access, and Durability

The durability of vehicle systems is extremely important. Hours of operation are short compared to commercial systems (160,000 miles at 40 mph = 4000 h), but the shock, vibration, corrosion, and other extreme conditions the vehicle receives or produces must not cause a malfunction or failure. Automotive systems have some unique physical parameters, such as engine motion, proximity to components causing adverse environments, and durability requirements, that are different from stationary systems. Relative to the rest of the vehicle, the engine moves both fore and aft because of inertia, and in rotation because of torque; this action is referred to as **engine rock**. Fore and aft movement may be as much as 0.5 in.; rotational movements at the compressor may be more than as 0.75 in. from acceleration and 0.5 in. from deceleration when the length to center of rotation is considered. Additionally, the need for components to survive bumper impacts of up to 5 mph leads to additional clearance and strength requirements. Vehicle components may also be exposed to many different types of chemicals, such as road salt, oil, hydraulic fluid (brakes and power steering), and engine coolant.

The automobile is also increasingly incorporating electrical and electronic components and functionality. This requires manufacturers to both limit the emissions of electrical signals from components as well as ensure that all components will work when subjected to these same types of emissions. Manufacturers' requirements for electromagnetic compatibility are increasingly stringent regarding the frequencies of radio and communication devices.

Wiring, refrigerant lines, hoses, vacuum lines, and so forth must be protected from exhaust manifold heat and sharp edges of sheet metal. Normal service items such as oil filler caps, power steering filler caps, and transmission dipsticks must be accessible. Air-conditioning components should not have to be removed to access other components.

Noise and Vibration

The temperature control system should not produce objectionable sounds. During maximum heating or cooling operation, a slightly higher noise level is acceptable. Thereafter, it should be possible to maintain comfort at a lower blower speed with an acceptable noise level. Compressor-induced vibrations, gas pulsations, blower motor vibration, and noise must be kept to a minimum. Suction and discharge mufflers are often used to reduce noise. Belt-induced noises, engine torsional vibration, and compressor mounting all require particular attention. Manufacturers have different requirements and test methods. Although it is almost impossible to predict vehicle sound level from component testing, a decrease in the sound and vibration energy at the source of noise will always decrease the noise level in vehicle (assuming there is not a shift in frequency), so most automobile manufacturers require continuous improvement in overall component sound level.

Vehicle Front-End Design

Front-end design affects performance of the climate control and engine cooling systems, especially at low speeds and at idle. The design should ensure that the air flowing into the front end through the bumper and/or grille does not bypass either the condenser or radiator from the sides, top, or bottom. Air will take the path of least resistance, and if not forced over the heat exchangers, it will usually bypass them. In a good design, the condenser and radiator are the same size, and should not have space between (Mathur 2005b). This eliminates the use of seals between the condenser and radiator. Typically, the front-end module has components in the following sequence: condenser, radiator, and fans (CRF); these systems are known as condenser-radiator-fan modules (CRFM). A good front-end design provides optimum performance for both air-conditioning and engine-cooling systems. Airflow over the front end couples these two systems; thus, performance of one system (e.g., air conditioning) influences the other system (engine cooling). This is most evident at idle.

In a typical design, sheet metal covers the entire area on the sides of the condenser. This prevents air from bypassing from either side of the condenser and radiator. To prevent recirculation of the hot engine compartment air at idle, the front bottom part of the front end is usually covered by sheet metal or plastic sheet. To limit recirculation on the top, a seal that sits on the cross frame when the hood is closed is usually added. This prevents recirculation of the hot engine compartment air to approximately the top and bottom thirds of the condenser. Without this, the condenser head pressure may increase greatly, further degrading system performance.

Enhanced R-134a systems, the next-generation AC system, require substantial changes to hardware and controls to achieve performance and energy requirement targets, although some of the strategies described here can be used to approach the targets.

AIR-HANDLING SUBSYSTEM

The in-cabin air-handling unit, commonly called an **air-conditioning module (ACM)**, provides air to the passenger cabin. It incorporates the following basic components: heater core, evaporator core, blower motor, air-distribution control, ram air control, body vents, and air temperature controls. In addition to the ACM, an air inlet plenum, distribution ducting, outlets, and body relief vents or drafters make up the complete air-handling subsystems. The evaporator core is a part of both the refrigeration and air-handling subsystems and forms the link between the two. The heater core is similarly the link with the heating subsystem.

The basic function of the air-handling system is as follows. The air intake valve allows air from either the exterior [taken directly from the air intake plenum or outside air (OA)] or the cabin to be recirculated to the fan. The fan then pumps air through the evaporator and into the temperature control door, which forces the air to either flow through or bypass the heater core to obtain the desired temperature. The air then moves to the distribution area of the module, where it is directed to one or more of the heater, ventilation, or defrost outlets. Air in the cabin then either is recirculated or exits out of the vehicle through body vents or drafter(s).

There are many variations on the basic ACM system. Common ones include regulating the air discharge temperature using coolant flow control and separating the ACM into two or more subcomponents to better fit the system in the vehicle.

Air Delivery Modes

There are three basic modes in most vehicles: heater, defroster, and air conditioning (or vent for vehicles without air conditioning). Typical mixed modes include bilevel, blend, and ambient.

Heater Mode. Heater mode is designed to provide comfort heating to vehicle occupants. Typical maximum heater airflow is 125

to 200 cfm for a mid-sized automobile. Heater air is generally distributed into the lower forward (foot) compartment, under the front seat, and up into the rear compartment. Air distribution near the floor also makes the vehicle more comfortable by providing slightly cooler air at breathing level. Because the supply air temperature is relatively high, direct impingement on the occupant is not desirable. Heater air exhausts through body leakage points.

Heater mode warms air in the vehicle above the dew points of the surrounding air and of the vehicle's glass. To prevent condensation from occupant respiration or from rain or snow tracked in, most vehicles sold in North America draw only OA when in heater mode and do not allow recirculation. However, some vehicle designs do allow recirculation, avoiding the higher cost of including the electric or vacuum actuation system necessary to prevent it.

Most vehicles also provide a small bleed of air (typically 15 to 25% of the total air flow) in heater (foot) mode to the windshield to isolate it from the car's interior. Properly designed, this prevents loss of visibility by window fogging under most conditions.

Defrost Mode. Defrost mode is provided to clear the windshield from frost and fog, both internally and externally. Typical maximum airflow for defrost systems is 150 to 200 cfm for a mid-sized automobile. Defrost mode requirements are given in the DOT's Federal Motor Vehicle Safety *Standard* (FMVSS) 103, which defines areas on the windshield for driver vision and a time frame in which they must be able to be cleared under extreme vehicle operating conditions. Most vehicles are also equipped with side window demisters that direct a small amount of heated air and/or air with lowered dew point to the front side windows. Rear windows are typically defrosted by heating wires embedded in the glass.

As in heater mode, to prevent windshield fogging, most vehicles built in North America prevent air from being recirculated in defrost mode. In addition, many vehicles automatically operate the air-conditioning system in defrost if the ambient temperature is above a threshold (usually around 40°F). This provides an extra assist and safety factor by lowering the dew point of the air exiting the ACM to below ambient temperature.

Air-Conditioning (or Panel) Mode. The air-conditioning mode is provided for occupant comfort cooling and to ventilate the vehicle. Typical airflow for panel mode is 200 to 300 cfm in a mid-sized car. Because of the lower temperature differentials in this mode, airflow is provided in such a way that direct impingement on the occupants can be achieved if desired. A minimum air velocity of 2000 fpm at the outlet is desired, to provide adequate comfort to occupants sitting in the front and rear of the cabin (Atkinson 2000). As discussed in the Design Factors section, the higher heat fluxes and higher initial temperature at vehicle start-up frequently require that the system be able to **spot cool**, providing the cooling airflow directly on the occupants, before lowering the overall cabin temperature. For these reasons, directability of the supply outlet on the occupants is very important. The air-conditioning system is designed to have sufficient capacity to bring the interior temperature down rapidly; panel outlets must also be positionable, to move the airflow off the occupants after a few minutes of operation.

Bilevel Mode. The most common mixed mode, bilevel mode is designed for moderate-temperature operation with high solar loading. The system provides air to both the lower outlets and the panel outlets. Typically, air from the panel outlets is 5 to 25°F cooler than the air from the lower outlets. This is to provide cooling to areas of the interior that have direct solar loading and to provide warm air to those that do not.

Blend Mode. The next most common mixed mode is blend mode, designed to provide a step between heater and defroster for times when extra heat is needed to keep the windshield clear but full defrost is not desired. A typical situation where blend mode is used is in city traffic during snowfall. The extra airflow to the windshield helps maintain a clear field of vision and still maintains adequate flow to lower outlets to keep occupants warm.

Outside Mode. This mode is also designed for mild ambients. It is intended to provide a relatively high total airflow through the cabin but without the high local air velocities of the other modes. Typically, vehicles with outside mode are also equipped with additional panel outlets not directed toward the occupants. The most common configuration provides air toward the ceiling from outlets in the middle of the dashboard.

Controls

The HVAC control head (i.e., the controls for the ACM and the refrigeration system) is located within easy reach of the driver and occupants. These controls must be easy to use and not distract the driver from the road. There are many variations of HVAC controls in automobiles, from the cable-controlled manual system to fully automatic systems that control the cockpit environment. The two main classifications are manual and automatic.

The **manual control** is typically the base system that provides control for mode, temperature valve position, air source, and air flow rate (blower speed). In addition to air-handling controls, the control head usually also has a button to engage the compressor (i.e., to turn on the AC system). Additional functions, such as rear defrost and seat heating controls, are frequently added to the control head. Although manual control provides a temperature mix door control, this is not a temperature control; it only controls the opening of the temperature valve and fixes the amount of air that bypasses the heater core. Therefore, if there is significant variation in ambient temperature or vehicle coolant temperature, the manual system will need to be adjusted. Manual systems typically have four or five blower speeds.

Automatic control uses a control unit and vehicle sensors to establish a comfortable thermodynamic environment for vehicle occupants. Sensors measure air inlet temperature, vehicle cabin temperature, and ACM discharge air temperature. The automatic control will then vary the mix door position, airflow rate, ACM mode, and air-conditioning compressor engagement. Some advanced systems measure cabin humidity for comfort control. Automatic systems usually have from 8 to 20 blower speeds.

Air quality control is also becoming available in many vehicles. Most of these systems assume that a vehicle will quickly pass through areas where the contamination source is prevalent. A sensor measures a **surrogate gas** (a gas that is not necessarily toxic but accompanies toxic gases that are more difficult to measure). When the surrogate gas is detected, the vehicle's air inlet door is positioned for recirculation to separate the occupants from the contamination source.

Air-Handling Subsystem Components

Air Inlet Plenum. The air inlet plenum (also called a **cowl**) is usually an integral part of the vehicle structure. There are two primary design considerations and several secondary design considerations for the air inlet plenum:

Primary

- Air that flows into the plenum should not be influenced by uncontrolled emissions from the vehicle systems; in other words, the plenum should be a source of clean air.
- The plenum should be located so that the aerodynamic effects of air movement over the vehicle increase pressure in the plenum, so when the vehicle operates with external air selected, air flows through the air-handling unit into the vehicle. This allows fresh air to flow through the vehicle and helps reduce the amount of external air that infiltrates into the vehicle from uncontrolled sources.

Secondary

- The pressure drop of the plenum should also be considered. Higher airflow pressure requires that more power be available to the ACM blower and fan to provide adequate airflow.

- Airflow at the entrance to the ACM's blower should be uniform. In many vehicle applications, a significant loss in efficiency is caused by unbalanced airflow into the fan.
- The air inlet plenum must also serve several other functions, such as water separation, protection from snow ingestion, and gross filtration (usually through a screen).
- The air inlet plenum must also be located such that when the vehicle is covered by snow, the plenum will still be able to furnish sufficient air to clear the windshield and provide fresh air to the occupants.

The air inlet plenum is usually located at the base of the windshield. If properly sealed from the underhood areas of the vehicle, this provides a relatively high-pressure and clean source of air. Major plenum design considerations include the following (Mathur 2005a).

Separation of Water Droplets from Airstream. It is important that openings in the plenum cover be sized carefully. Openings that are too small result in a higher pressure, which reduces airflow and increases noise. Reduced airflow increases window fogging and significantly decreases occupants' perceived comfort. Surface tension can also cause rainwater to plug small openings and get sucked into the plenum when the blower is turned on in OA mode. On the other hand, very large openings can allow snow or sleet inside, where it can accumulate and ultimately block the path of airflow. Plenum cover opening sizes should be optimized to address both these issues.

Water droplets follow the air trajectory inside the plenum. Removing the droplets requires changing the airflow direction: because their momentum is greater, the droplets do not change direction but instead hit the sheet metal wall and then drain to the bottom of the plenum channel. Otherwise, filters may become saturated with water. Adding baffles inside the plenum channel can change airflow direction, but also increases air pressure drop, which affects both airflow rate and noise levels. Angling baffles in the flow direction helps alleviate this pressure drop increase.

Expanding the plenum's cross-sectional area is another way of removing water droplets from the air stream, but is not always possible because of space limitations. This is a good approach, though, around the wiper motor and linkages, which are housed inside the plenum channel and significantly reduce airflow area.

Snow Separation. As discussed previously, plenum cover opening size is crucial in keeping precipitation out of the plenum. Even with an optimum cover design, though, accumulated snow must be removed before the blower unit is turned on in OA mode. Otherwise, dry, powderlike snow could enter the plenum and end up on the filter, saturating it and causing fogging issues.

Hard snow over the plenum cover is difficult to remove and significantly reduces airflow when the blower is turned on. As air flows over the openings, some of the ice is directly evaporated into the air stream by sublimation, increasing window fogging. To address this situation, some plenum cover openings in newer cars are under the hood, allowing some airflow into the cabin in this situation. Note, however, that this approach could be lethal in old cars that leak exhaust gases from faulty gaskets under the hood.

Distribution Ducting. Air from the air-handling unit is distributed to various areas of the vehicle through ducting. Typically, the main trunk duct exits the ACM near the middle of the dashboard. Ducting carries the air from this central location to the extremes of the instrument panel, the floor, and even the rear seat (if so equipped). The design goal for the distribution ducting is to distribute air throughout the vehicle with as little pressure drop as possible, to provide sufficient airflow to the various outlets for occupant comfort. This goal is frequently compromised by the tight packaging constraints in modern vehicles. Ducts should be designed with no sharp edges inside the airflow stream, which could increase airflow rush noise.

Outlets. There are typically defrost, heater, side window, and panel air outlets in a vehicle. The defrost air outlet is located on top the instrument panel to distribute air to clear the windshield of frost and fog as quickly and efficiently as possible. Heater outlets are located on the bottom of the instrument panel to spread warm air over the floor of the vehicle. Panel outlets are designed to provide cool air to the occupants. The importance of panel outlets should not be underestimated. The ability to achieve direct air impingement on occupants with little diffusion is very important to comfort after a vehicle has been inoperative during extremely hot summer conditions. Likewise, it is important to be able to direct the cool air away from occupants after the interior begins to cool down. The air pressure drop in the vent outlet changes as the direction of the vane or blade is changed, and can result in reduced airflow. This is necessary to direct the airflow over the desired area of the passenger. The ability to direct the jet air and reach the occupants under all conditions can result in satisfied consumers; the lack of this ability has resulted in dissatisfied consumers even in vehicles with exceptional airflow and capacity.

Body Relief Vents or Drafters. Body relief vents or drafters are designed to ensure airflow through the vehicle from front to rear. The drafters are located inside the trunk, under the carpet, on the sides near the wheel wells. Air flows from the cabin into the trunk through parcel shelf openings (holes that facilitate airflow from cabin to trunk), and then between the sheet metal and carpet to the drafters. Typically, they are effectively low-pressure check valves, designed to allow airflow out of the vehicle when cabin pressure is above the local exterior pressure and to prevent air infiltration when the local exterior pressure is above that of the interior (i.e., when the vehicle is using recirculated air as the air source). Relief vents should be located where they will cause the airflow inside the body to cover all occupant locations inside the vehicle.

A small number of openings in the vehicle body are required for wires, cables, and various attachment features; therefore, the body relief vent does not typically need to be sized large enough to exhaust the total airflow through the vehicle.

Heater Core. The heat transfer surface in an automotive heater is generally either copper/brass cellular, aluminum tube and fin, or aluminum-brazed tube and center. Each of these designs is in production in straight-through, U-flow, or W-flow configurations. The basics of each of the designs are outlined as follows:

- The **copper/brass cellular** design is not used frequently in new vehicles. It uses brass tube assemblies (0.006 to 0.016 in. wall thickness) as the water course, and convoluted copper fins (0.003 to 0.008 in. thick) held together with a lead/tin solder. The tanks and connecting pipes are usually brass (0.026 to 0.034 in. wall thickness) and again are attached to the core by a lead/tin solder.
- The **aluminum tube-and-fin** design generally uses round copper or aluminum tubes, mechanically joined to aluminum fins. U tubes can take the place of a conventional return tank. The inlet/outlet tank and connecting pipes are generally plastic and attached to the core with a rubber gasket.
- The **aluminum-brazed tube-and-center** design uses flat aluminum tubes and convoluted fins or centers as the heat transfer surface. Tanks are either plastic and clinched onto the core or aluminum and brazed to the core. Connecting pipes are constructed of various materials and attached to the tanks a number of ways, including brazing, clinching with an O ring, fastening with a gasket, and so forth. Almost all original equipment manufacturers (OEMs) currently use brazed-aluminum heater cores (Jokar et al. 2004).

Air-side design characteristics include pressure drop and heat transfer. The pressure drop of the heater core is a function of the fin/louver geometry, fin density, and tube density. Capacity is adjusted by varying the face area of the core to increase or decrease

the heat transfer surface area, adding coolant-side turbulators, or varying air-side surface geometry for turbulence.

Evaporator. Automotive evaporator materials and construction include (1) copper or aluminum tube and fin; (2) brazed-aluminum plate and fin, also known as a laminate evaporator; and (3) brazed serpentine tube and fin. This section addresses the air-side design of the evaporator. Air-side design parameters include air pressure drop, capacity, and condensate control.

A laminate evaporator consists of a number of stamped plates and louvered fins. The plates have clad material on both sides. The plates and fins are stacked and then either vacuum-brazed or controlled-atmospheric brazed (CAB). The advantage of using CAB is that it is a continuous process, whereas vacuum brazing is a batch process. When brazed, the plate forms internal flow passages for refrigerant. The plates have diagonal ribs (or multiple dimples) to augment heat transfer and provide strength, and central partitioning ribs that facilitate reversal of refrigerant flow. These evaporators may have tanks on both ends or on one end only. For the same airflow area, a single-tank evaporator has better performance than a double-tank evaporator, because the available heat transfer area is greater (i.e., the ratio of total heat exchange area to total volume of the core is higher for evaporators with single tanks). Laminate evaporators typically have four to six refrigerant passes. Two-phase refrigerant enters the evaporator through the inlet pipe, and vapor exits the evaporator through the outlet pipe. Two-phase refrigerant enters the evaporator through the tank and moves downward in multiflow channels (or plates) in pass 1 and then flows upward in pass 2. The refrigerant reaches the tank section at the top and then flows downward in pass 3, flows upward in pass 4, and exits the evaporator as vapor (Mathur 2000a, 2001b, 2002, 2003a).

Typically, an ACM is designed to provide the airflow required to provide cooling for the vehicle. The combination of airflow, maximum allowable current draw for the blower motor, size constraints on the ACM, and ductwork act together to establish a required evaporator air-side pressure-drop characteristic. The air-side pressure drop of the core is typically a function of fin spacing, louver design, core depth, and face area. This characteristic varies with accumulation of condensate on the core, so adequate leeway must be allowed to achieve target airflow in humid conditions.

Conditions affecting evaporator capacity are different from those in residential and commercial installations in that the average operating time, from a hot-soaked condition, is less than 20 min. Inlet air temperature at the start of operation can be as high as 160°F, but decreases as the vehicle duct system is ventilated. Capacity requirements under multiple conditions must be considered when sizing an automotive evaporator, including steady-state operation at high or low speeds, and a point in a cooldown after an initial vehicle hot soak. Some of these requirements may also be set in recirculating conditions where the temperature and humidity of inlet air decrease as the car interior temperature decreases.

The evaporator load also has a slightly higher sensible heat portion than indicated by ambient temperature. The heat gain from the vehicle and the temperature rise across the blower motor must be considered when sizing the evaporator.

During longer periods of operation, the system is expected to cool the entire vehicle interior rather than just produce a flow of cool air. During sustained operation, vehicle occupants want less air noise and velocity, so the air quantity must be reduced; however, sufficient capacity must be preserved to maintain satisfactory interior temperatures.

Condensate management is very important within a motor vehicle. In the process of cooling and dehumidifying the air, the evaporator extracts moisture from the air. It is imperative that condensate be prevented from entering the vehicle interior as a liquid, because this will damage the vehicle. This moisture should be carried out of the vehicle and not allowed to collect inside the ACM (Mathur 2000b). A distinct odor can be identified in many cars that have
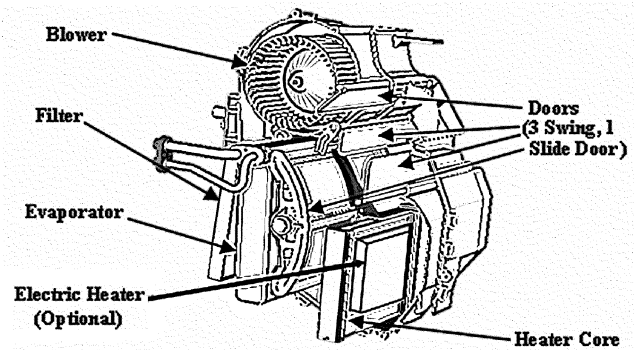

Fig. 2   Integrated HVAC Unit

plugged condensate drain holes. This odor is given off by common organisms, present almost everywhere, that grow in warm, moist environments.

Condensate management includes the following design objectives (Mathur 1999a):

- Ensure that moisture coming off the evaporator is in large enough droplets that it is not carried by the airstream (a combination of low velocity at the exit of the core and adequate ability of the core to allow surface tension to gather the water)
- Allow sufficient fin spacing for adequate condensate drainage
- Allow a large enough sump so that all water coming off the core can be collected for a short period of time when vehicle-maneuvering forces push water away from the drain
- Provide sufficient slope to the drain area so that water flows to the drain rather than collecting in the case
- Have a sufficient cross section in the drain so that water does not back up into the module, taking into account the fact that ACM interior pressure is usually 1 to 2 in. of water above the exterior pressure

Vehicle attitude (slope of the road and inclines), acceleration, and deceleration should also be considered because these factors have a significant effect on the drain system design. Drains can become plugged not only by contaminants but also by road splash.

Location of HVAC Unit. The HVAC unit consists of the blower intake unit, cooling unit, and a heater unit. The system also has several ducts that feed air to different circuits. These units are mounted inside the **cockpit module (CPM)**. U.S.-made vehicles use **modular design**, in which the blower, evaporator, and heater are individual units. **Integrated units** (Figure 2) that combine all three functions into one component have been developed, but their design is complex.

Blower Motor and Fans. Airflow in an automobile must provide sufficient cooling air to passengers in both the front and rear seats. Designs for the blower motor and fan, which must fit in a relatively small space, are frequently a compromise between packaging, mass, airflow, and efficiency. Virtually all fans used in automotive ACMs are centrifugal, with fan diameters from 5.5 to 8 in. Typical motor current draws vary from 14 to 25 A, depending on factors affecting optimization of the particular application. Both forward- and backward-inclined fan blades have been used.

Automotive systems are achieving a significantly improved level of comfort. Much of this is due to reductions in the noise, vibration, and harshness (NVH) characteristics of the interior. This continued effort has required continuous improvement in the NVH characteristics of blower motor and fan assemblies. During integration of the blower motor and fan into the module, careful attention must be paid to any type of vibrational excitation the fan may impart to the ACM and other underdash components.

Electronic Blower Speed Control. Historically, the blower motor speed control was simply a selector switch that selected either from direct battery voltage at the blower motor or from one of two or more resistors in series with the blower motor to reduce voltage. In general, the lowest airflow selectable is usually driven by the need to provide adequate air pressure to cool the blower motor. Modern blower motor speed controls incorporate essentially infinite speed control using devices such as **pulse-width modulating (PWM)** controllers. The newer devices are usually found on upscale vehicles using automatic climate control systems, which reduce energy consumption and increase fuel efficiency. When incorporating devices such as PWMs into a vehicle system, careful attention needs to be paid to radio frequency interference because of the necessary proximity of all the electronics in a vehicle.

Valves. The typical ACM has valves for the air inlet source, temperature control (heater air bypass), and mode control. Some vehicles also have a ram air door, used to reduce ram effect at high speeds and provide consistent airflow. Door/valve designs are integral to the ACM design. Door types include flag style, rotary, guillotine, slider, and film valves. The optimal door type is almost always a function of the space in which a module must fit.

Actuators. Actuators on ACMs are usually cable, electric, and/ or vacuum. **Cable-based actuation** is usually the least expensive and most frequently found in entry-level vehicles. The valving system must be designed to retain a position with minimal restraining torque, have smooth operation with essentially constant torque level, and have minimal torque required to move the valve(s). There must be a suitable cable path from the HVAC controls to the module. Cable actuation does not allow electronic control of the air-conditioning system or an interlock to ensure outside air is selected in defrost mode.

The norm for U.S. automobiles 20 years ago, **vacuum actuation**, has been replaced by electronic actuators. Vacuum actuators can provide only three position controls per actuator and require a cross-sectional area for the diaphragm proportional to the load on the door. The vacuum source is the vehicle's engine intake air manifold. Although this provides a powerful control at engine idle, a great deal of variation exists in the working pressure differential, and must be taken into account in system design.

Electric actuators can control the ACM electronically and are available in variety of shapes. The possibility of linear positions allows for multiple modes, with one actuator on several doors, using a cam system. They also isolate the operator from torque variations, allowing the ACM to be optimized for other performance criteria.

Air Inlet. The air inlet interfaces the ACM with the vehicle body. If not accomplished upstream, it is necessary for the air inlet to separate out water that may have been ingested from rain, carwashes, etc. It also provides the selection of either outside air or air recirculated from the passenger compartment. On upscale performance vehicles, the ram air door is also located here. A primary design criterion for the air inlet is to provide proper flow patterns at the inlet of the blower motor. In many applications this is compromised to fit the ACM into the vehicle. The result is either turbulence or misdistribution of air into the fan, causing noise and lower efficiency.

Mode Control. Air distribution is usually done at the ACM by one or more valves directing air to the desired vehicle outlets. This system may provide several discrete modes or a continuous variation from one mode to the next. ACM valving must be designed to work with the distribution ductwork and provide the desired air distribution to the occupants.

Air Distribution. Air distribution must be done in a way that minimizes pressure loss, thermal lag, and heat gain. Ductwork is usually designed around the other underdash components, and frequently must follow a difficult path. The air for all outlets starts at one basic plenum pressure, and variations in pressure drop versus flow rate from side to side in the vehicle must be minimized to pro-

vide even airflow to both driver and passengers. Because of the instrument cluster in front of the driver and devices such as airbags, ductwork is almost never laterally symmetrical. Computational fluid dynamics is used to ensure proper air distribution design.

Air Filter. Air filters are increasingly common, typically located in either the air inlet plenum or the ACM. Filters may be particulate, charcoal, or both; they require regular service to prevent clogging and ensure proper system function. Removal of contaminants (e.g., pollen) may also be aided by condensate on evaporator surfaces. The concentration of the volatile organic compounds (VOCs) from the vehicle's interior (plastic parts, carpet, adhesive, etc.) along with tailpipe emissions (NO_x, CO, hydrocarbons) from automobiles, buses, and trucks can be reduced by using carbon filters. These filters should be replaced regularly, based on driving conditions, because a dirty filter can be the largest source for polluting cabin air.

HEATING SUBSYSTEM

The primary heat source is the vehicle's engine. Coolant from the engine cooling system circulates through the heater core. Modern efficiency and emissions improvements have led to many types of supplemental heating produced today, including fuel-fired heaters, refrigerant heat pumps, electrical heaters, and heat storage systems.

The heater core must be designed to work within the design of the engine cooling system. Engine coolant pressure at the heater core inlet ranges up to 40 psig in cars and 55 psig on trucks.

Modern antifreeze coolant solutions have specific heats from 0.65 to 1.0 Btu/lb·°F and boiling points from 250 to 272°F (depending on concentration) when a 15 psi radiator pressure cap is used.

Controls

Engine coolant temperature is controlled by a thermostatically operated valve that remains closed until coolant temperature reaches 160 to 205°F. Coolant flow is a function of pressure differential and system restriction, but typically ranges from 0.6 gpm at idle to 10 gpm at higher engine speed. Coolant temperature below 160°F is not desirable, because it cannot meet occupants' comfort requirements. The mechanical pump should be able to deliver sufficient coolant flow, even at idle.

Components

The minimal components of the heating subsystem are the coolant flow circuit (water pump) and temperature control, both provided by the vehicle's engine; the heater core (part of the ACM); and coolant hoses.

REFRIGERATION SUBSYSTEM

Cooling is almost universally provided by a vapor cycle system. The thermodynamics of a vapor cycle system are described in Chapter 1 of the 2005 *ASHRAE Handbook—Fundamentals*. The automotive system is unique in several ways.

Refrigeration capacity must be adequate to bring the vehicle interior to a comfortable temperature and humidity quickly and then maintain it during all operating conditions and environments. A design may be established by mathematical modeling or empirical evaluation of known and predicted factors. A design tradeoff in capacity is sought relative to criteria for vehicle weight, component size, and fuel economy. Automotive system components must meet internal and external corrosion, pressure cycle, burst, and vibration requirements.

Refrigerant-based system equipment is designed to meet the recommendations of SAE *Standard* J639, which includes several requirements for refrigerant systems. To be compliant, a system must have

• A high-pressure relief device

- Burst strength (of components subjected to high-side refrigerant pressure) at least 2.5 times the venting pressure of the relief device
- Electrical cutout of the clutch coil before pressure relief to prevent unnecessary refrigerant discharge
- Low-pressure-side components with burst strengths in excess of 300 psi

The relief device should be located as close as possible to the discharge gas side of the compressor, preferably in the compressor itself.

Controls

Refrigerant Flow Control. Cycling-clutch designs are the most common mechanisms for controlling refrigerant flow. Schematics for the two most common versions of this design are shown in Figures 3 and 4. The clutch is cycled by either a thermostat that senses evaporator temperature or a pressure switch that senses evaporator pressure. This thermostat or pressure switch serves two functions: it prevents evaporator icing, and it maintains a minimum refrigerant density at the inlet of the compressor, preventing overheating. Discharge air temperature is then increased, if necessary, by passing some (or all) of the evaporator outlet air through the heater core.

The clutch-cycling switch disengages at about 25 psig and engages at about 45 psig. Thus, the evaporator defrosts on each off-cycle. The flooded evaporator has enough thermal inertia to prevent rapid clutch cycling. It is desirable to limit clutch cycling to a maximum of six cycles per minute because a large amount of heat is generated by the clutch at engagement. The pressure switch can be used with a thermostatic expansion valve in a dry evaporator if the pressure switch is damped to prevent rapid cycling of the clutch.

Cycling the clutch sometimes causes noticeable surges as the engine is loaded and unloaded by the compressor. This is more evident in cars with smaller engines. This system cools more quickly and at lower cost than a continuously running system.

For vehicles where clutch cycling is unwanted because of engine surge, or for high-end vehicles where no perceptible temperature swing is allowable, variable-displacement compressors are available, controlled either electronically or pneumatically.

In the **pneumatically controlled compressor**, a sensor (usually located in the compressor body) varies the compressor displacement so that a constant pressure is maintained at the compressor inlet. This provides a nearly uniform evaporator temperature under varied loading conditions. This type of system causes no perceptible engine surge with air-conditioning system operation.

The **electronically controlled variable-displacement compressor** opens up many possibilities for systems optimization. This type of compressor allows reduced reheat control, and evaporator temperature is maintained at such a level that comfort is achieved with less fuel consumption. A wide range of control schemes using electronically controlled variable-displacement compressors are being developed.

Other Controls. A cycling switch may be included to start an electric fan when insufficient ram air flows over the condenser. Also, output from a pressure switch or transducer may be used to put the ACM into recirculation mode, which reduces head pressure by reducing the load on the evaporator. Other possibilities include a charge loss/low-ambient switch, transducer evaporator pressure control, and thermistor control.

Components

Compressor. Piston compressors dominate the automotive market, although scroll and rotary vane types are also significant. For detailed information on compressor design, see Chapter 34 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*. Figure 5 illustrates basic automotive compressor types. The typical automotive compressor has the following characteristics:
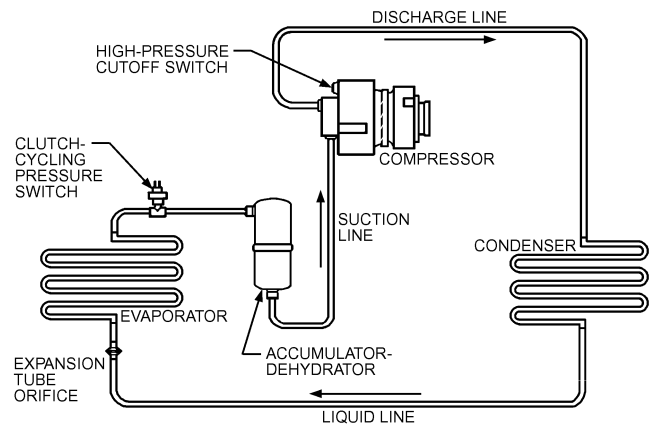
Fig. 3   **Clutch-Cycling System with Orifice Tube Expansion Device**
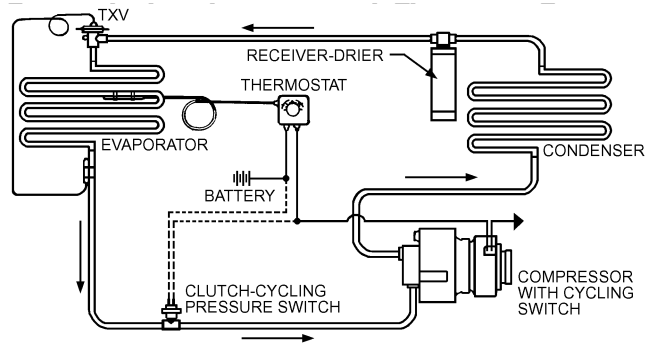
Fig. 4   **Clutch-Cycling System with Thermostatic Expansion Valve (TXV)**

- **Displacement.** Fixed-displacement compressors have displacements of 6.1 to 12.6 in^3/rev. Variable-displacement piston compressors typically have a minimum displacement of about 6% of their maximum displacement. A typical variable-capacity scroll compressor has a maximum displacement of 7.3 in^3/rev and a minimum displacement of 10% of the maximum.
- **Physical size.** Fuel economy, lower hood lines, and more engine accessories all decrease compressor installation space. These features, along with the fact that smaller engines have less accessory power available, promote the use of smaller compressors.
- **Speed range.** Most compressors are belt-driven directly from the engine; they must withstand speeds of over 8000 rpm and remain smooth and quiet down to 500 rpm. The drive ratio from the vehicle engine to the compressor typically varies from 1:1 to 2:1. In the absence of a variable drive ratio, the maximum compressor speed may need to be higher to achieve sufficient pumping capacity at idle.
- **Torque requirements.** Because torque pulsations cause or aggravate vibration problems, it is best to minimize them. Minimizing peak torque benefits the compressor drive and mount systems. Multicylinder reciprocating and rotary compressors aid in reducing vibration. An economical single-cylinder compressor reduces cost; however, any design must reduce peak torques and belt loads, which are normally at a maximum in a single-cylinder design.
- **Compressor drives.** A magnetic clutch, energized by power from the vehicle engine electrical system, drives the compressor. The clutch is always disengaged when air conditioning is not required. The clutch can also be used to control evaporator temperature (see the section on Controls).

CONSTRUCTION OUTLINE (CROSS SECTION)

2 CYLINDERS

A. CRANK TYPE

3 + 3 CYLINDERS

B. SWASH PLATE TYPE

5 CYLINDERS

C. WOBBLE PLATE TYPE

5 × 2 CHAMBERS

D. VANE ROTARY

Fig. 5   Basic Compressor Designs for Automotive Application

(A) SERPENTINE CONDENSER   (B) PARALLEL-FLOW CONDENSER

Fig. 6   Basic Automotive Condensers
(Mathur 1999b)

Condenser. Automotive condensers are generally of the following designs: (1) tube-and-fin with mechanically bonded fins; (2) serpentine tube with brazed, multilouvered fins; or (3) header extruded tube brazed to multilouvered fins, also known as parallel-flow (PRF) condensers, which are primarily used in automotive applications (Figure 6). To prevent air bypass, condensers generally cover the entire radiator surface. Aluminum is popular for its low cost and weight.

Operation of Parallel-Flow Condenser. A PRF condenser consists of flat tubes that have multiple flow channels. Refrigerant is supplied directly to the tubes through the header. Louvered fins are currently used in automotive heat exchangers. A typical refrigerant tube has 0.08 in. thick wall with tube widths ranging from 0.71 to 0.87 in., with 6 to 12 flow channels; smaller tubes are also available. Flat tubes have less projected frontal area to the airstream; this results in lower air-side pressure drop. Performance of a parallel-flow condenser is superior to that of a serpentine condenser (Mathur 1998a), because the refrigerant is distributed in multiple tubes. For the same reason, refrigerant pressure drop in a PRF condenser is also much smaller.

Typically, in a PRF condenser, the first pass (see Figure 6B) has the largest number of refrigerant tubes, with fewer tubes in each successive pass. This is because the specific volume of superheated vapor coming out from the compressor is very large, and the density of refrigerant vapor is very small. This results in very high vapor velocities ($m = \rho AV$) in the tubes. At this condition, the refrigerant void fraction is unity, which results in a very high pressure drop. Therefore, this high volumetric flow must be subdivided into a large number of tubes to lower refrigerant velocities, and thus pressure drop. At some point along the condenser, refrigerant vapor temperature equals saturated temperature, and wall temperature falls below saturation temperature. At this time, condensation starts and the average density of the two-phase refrigerant mixture starts to increase. With the increase of the two-phase mixture density, the average refrigerant velocities start to decrease. This affects the condensation heat transfer coefficient and frictional pressure drop. When all vapors are condensed, the refrigerant flow becomes single-phase liquid. At this condition, the refrigerant flow velocity is lowest, which yields lower pressure drop. Thus, the last pass has the fewest tubes.

Condenser Design. Condensers must be properly sized. An undersized condenser results in high discharge pressures that reduce compressor capacity, increase compressor power requirements, and result in poorer discharge air temperatures. When the condenser is in series with the radiator, the air restriction must be compatible with the engine cooling fan and engine cooling requirements. Generally, the most critical condition occurs at engine idle under high-load conditions. An undersized condenser can raise head pressures sufficiently to stall small-displacement engines.

An oversized condenser may produce condensing temperatures significantly below the engine compartment temperature. This can

- **Variable-displacement compressors.** Both axial and wobble plate variable-displacement compressors are available for automobile air conditioning. The angle of the plate changes in response to the suction and discharge pressure to achieve a constant suction pressure just above freezing, regardless of load. A bellows valve or electronic sensor-controlled valve routes internal gas flow to control the angle of the plate. A variable-displacement compressor reduces compressor power consumption, improving fuel efficiency. These compressors improve dehumidification and comfort, have low noise and vibration, and have high reliability and efficiencies.
- **Noise, vibration, and harshness.** With decreasing mass and increasing environmental quality in automobiles, compressor design is increasingly driven by NVH concerns. Vibrational input to the structure, suction and discharge line gas pulsations, and airborne noise must all be minimized. NVH minimization is now the main impetus behind most continuous improvement efforts in the automotive compressor industry.
- **Mounting.** Compressor mounts are an important part of a successful integration of a compressor into a vehicle system. Proper mounting of the compressor minimizes structural resonances and improves the NVH characteristics of any compressor.

Compressor Oil Return. It is important that there are no areas where the lubrication oil can accumulate (Mathur 2004a). At part-load conditions, refrigerant velocities should be high enough to ensure oil return to the compressor. The presence of oil in the system affects heat exchanger performance (Mackenzie et. al. 2004). Some new compressors have a built-in oil separator.

result in evaporation of refrigerant in the liquid line where the liquid line passes through the engine compartment (the condenser is ahead of the engine and the evaporator is behind it). Engine compartment air has been heated not only by the condenser but by the engine and radiator as well. Typically, this establishes a minimum condensing temperature between 10 and 30°F above ambient. Liquid flashing occurs more often at reduced load, when the liquid line velocity decreases, allowing the liquid to be heated above saturation temperature before reaching the expansion valve. This is more apparent on cycling systems than on systems that have a continuous liquid flow. Liquid flashing is audibly detected as gas enters the expansion valve. This problem can be reduced by adding a subcooler or additional fan power to the condenser.

Internal pressure drop should be minimized to reduce compressor power requirements. Condenser-to-radiator clearances as low as 0.25 in. have been used, but 0.5 in. is preferable. Primary-to-secondary surface area ratios vary from 8:1 to 16:1. Condensers are normally painted black so that they are not visible through the vehicle's grille.

Placing the condenser ahead of the engine-cooling radiator not only restricts air but also heats the air entering the radiator. Air conditioning increases requirements on the engine-cooling system, which requires an increase in either radiator capacity, engine-cooling airflow, or both. Radiator capacity can be increased by adding fins, depth, or face area or by raising pump speed to increase coolant flow. Increasing coolant velocity is not normally done because it may cause excessive tube erosion or cavitation at the coolant pump inlet. With this configuration, engine-cooling airflow requirements increase; they are met by increasing fan size, number of blades, blade width, blade pitch, by the addition of a fan shroud, or a combination of these items. Increases in fan speed, diameter, and pitch raise the noise level and power consumption. For engine-driven fans (primarily used on trucks), temperature- and torque-sensitive drives (viscous drives or couplings) or flexible-blade fans reduce the increases in noise that come with the higher power. Virtually all automobiles rely on airflow produced by the forward motion of the car to reduce the amount of air the engine-cooling fan must move to maintain adequate coolant temperatures. As vehicle speed increases, fan requirements drop, and electric fans are deenergized or engine-driven fans are decoupled by the action of the viscous drive.

Because each vehicle is optimized for its intended market segment, some vehicles have a side-by-side condenser and radiator, each with its own motor-driven fan. This eliminates the effect of the condenser on the engine cooling air inlet temperature but causes other issues with fan control and potential engine bay recirculation when one system is energized and the other is not.

Subcooled Condensers. There is a trend of using subcooled condensers to improve overall air-conditioning system performance. Thermodynamically, by increasing subcooling at the end of the condenser (on a *p-h* diagram), the overall system performance is increased (see Chapter 1 of the 2005 *ASHRAE Handbook—Fundamentals*), because the overall evaporator enthalpy difference (i.e., the difference in enthalpies between evaporator outlet and inlet) increases. Figure 7 shows a conventional PRF condenser in which refrigerant flows out from the condenser to the receiver-drier. In the subcooled PRF condenser, refrigerant from the second-last pass flows to the receiver-drier and then back to the condenser in the last path to subcool the refrigerant. In a subcooled PRF condenser, the size of the receiver-drier can be reduced because the condenser has more liquid refrigerant.

Hoses. Rubber hose assemblies are installed where flexible refrigerant transmission connections are needed because of relative motion between components (usually caused by engine rock) or where stiffer connections cause installation difficulties and noise transmission. Refrigerant permeation through the hose wall is a design concern. Permeation occurs at a reasonably slow and predictable rate that increases as pressure and temperature increase. Hose

(A) CONVENTIONAL SYSTEM   (B) SUBCOOLED SYSTEM
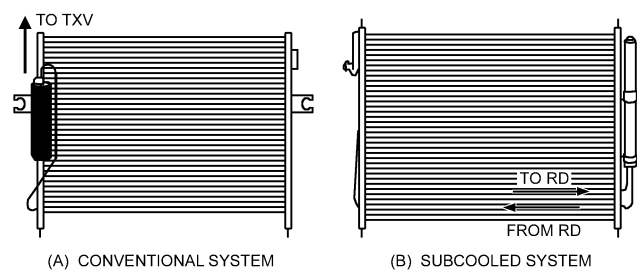
Fig. 7   Conventional and Subcooled PRF Condenser Designs

with a nylon core (**barrier hose**) is less flexible, has a smaller OD, is generally cleaner, and allows practically no permeation. However, because it is less flexible, it does not provide damping of gas pulsations as does other hose material. It is recommended for R-134a.

Reducing Noise and Vibration. Typically, the refrigerant lines connected to the compressor (both suction and discharge sides) require hose that is a composite of rubber, nylon, and aluminum tube. This is necessary to eliminate or reduce transmission of clutch engagement noise to the cabin by metallic tubes. In some cases, mufflers are also used to reduce noise and vibrations from refrigerant flow.

Suction and discharge hoses and high-pressure liquid lines have connections for charging ports, sensor, and for service. Brackets and clips are also attached to the hoses and refrigerant lines to position and support the AC lines.

Expansion Devices. Virtually all modern automobiles use either a thermostatic expansion valve (TXV) or an orifice tube (or both, for dual evaporator systems) as the expansion device (see Chapter 44 of the 2006 *ASHRAE Handbook—Refrigeration* for more on these devices). Schematics of systems that use these devices are provided in the Controls section.

Automotive TXVs operate in the same manner as those for commercial HVAC systems. Both liquid- and gas-charged power elements are common. Internally and externally equalized valves are used as dictated by system design. Externally equalized valves are necessary where high evaporator pressure drops exist. A bulbless expansion valve, usually block-style, that senses evaporator outlet pressure without the need for an external equalizer is now widely used. TXV systems use a receiver-drier-filter assembly for refrigerant and desiccant storage.

Because of their low cost and high reliability, orifice tubes have become increasingly popular with automotive manufacturers. Developing an orifice tube system requires that components be matched to obtain proper performance. The orifice tube is designed to operate at 90 to 95% quality at the evaporator outlet, which requires a suction line accumulator to protect the compressor from floodback and to maintain oil circulation. Because the orifice tube does not fully use the latent heat in the refrigerant systems, orifice-tube systems generally require higher refrigerant flow than TXV systems to achieve the same performance. However, an orifice tube ensures that the compressor receives a continuous flow of cool refrigerant from the accumulator, offering benefits in compressor durability over a TXV system. Orifice-tube systems use an accumulator-drier-filter for refrigerant and desiccant storage.

Receiver-Drier-Filter Assembly. A receiver-driver is installed in the AC loop on the high-pressure side downstream of the condenser. Several types of desiccant are used, the most common of which is spherical molecular sieves; silica gel is occasionally used. The unit typically has desiccant either in a bag or cartridge, or sandwiched between two plates. The receiver-drier (1) serves as a reservoir for refrigerant from part- to full-load operating conditions, (2) removes moisture from the system, (3) filters out debris headed for the TXV, and (4) only allows liquid refrigerant to enter the TXV
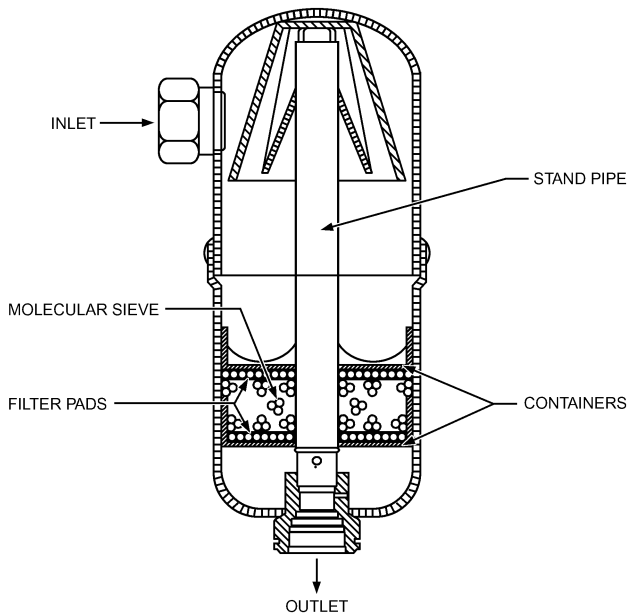
INLET →

STAND PIPE

MOLECULAR SIEVE —

FILTER PADS —

CONTAINERS

OUTLET

Fig. 8 Schematic of Typical Accumulator-Dehydrator

(liquid is removed from the top of the unit, and comes from the bottom via a tube connected to the top fitting).

The receiver-drier assembly accommodates charge fluctuations from changes in system load. It accommodates an overcharge of refrigerant to compensate for system leaks and hose permeation. The assembly houses the high-side filter and desiccant. Mechanical integrity (freedom from powdering) is important because of the vibration to which the assembly is exposed. For this reason, molded desiccants have not obtained wide acceptance. Moisture retention at elevated temperatures is also important. The rate of release with temperature increase and the reaction while accumulating high concentration should be considered. Design temperatures of at least 140°F should be used.

Receivers are usually (though not always) mounted on or near the condenser. They should be located so that they are ventilated by ambient air. Pressure drop should be minimal. Typically, a receiver-drier has a pressure switch or a pressure transducer installed that controls AC system operation at high pressure.

Suction Line Accumulators. A suction line accumulator is required with an orifice tube to ensure uniform return of refrigerant and oil to the compressor, to prevent slugging, and to cool the compressor. It also stores excess refrigerant. A typical suction line accumulator is shown in Figure 8. A bleed hole at the bottom of the standpipe meters oil and liquid refrigerant back to the compressor. The filter and desiccant are contained in the accumulator because no receiver-drier is used with this system.

Evaporator. The evaporator connects the air side of the air-conditioning system to the refrigerant side. Design aspects for the air side are discussed in the Air-Handling Subsystem section. The primary design consideration for the refrigerant side of the evaporator is low pressure drop. Because the evaporator operates at saturation, higher-pressure-drop evaporators cause nonuniform discharge temperatures unless they are designed with careful attention to pass arrangement. The space available in an automotive system does not allow for distribution manifolds and capillary tube systems outside of the evaporator envelope; this must be done within the evaporator itself.

Automotive evaporators must also mask the variation in compressor capacity that occurs with accelerating and decelerating. To avoid undesirable temperature splits, sufficient liquid refrigerant

should be retained at the last pass to ensure continued cooling during acceleration.

High refrigerant pressure loss in the evaporator requires externally equalized expansion valves. A bulbless expansion valve, called a block valve, provides external pressure equalization without the added expense of an external equalizer. The evaporator must provide stable refrigerant flow under all operating conditions and have sufficient capacity to ensure rapid cooldown of the vehicle after it has been standing in the sun.

Auxiliary Evaporators. Many sport-utility vehicles, vans, and limousines are equipped with auxiliary or secondary air-conditioning modules located to cool rear-seat passengers. These system extensions provide some unique challenges. Most of these systems operate only when there are passengers in the rear space. Consequently, sometimes there is refrigerant flow through the primary ACM and none through the secondary. Careful attention should be paid to refrigerant plumbing to avoid refrigerant and oil traps in the suction line. The auxiliary suction line must never allow liquid oil to run downhill from the front system when there is no flow to carry it back to the accumulator-dehydrator. Designing highly efficient oil separators into the line set results in frequent compressor failure.

Refrigerants and Lubricants. The 1997 Kyoto Protocol identified the almost universally used R-134a as a global warming gas. This has led to a search for alternatives (Giles et al. 1997) among vehicle manufacturers and their suppliers. The leading contenders today are carbon dioxide (Bhatti 1997; Mathur 1998b, 1999c, 2000c, 2000d), hydrocarbon-based refrigerants (most concepts using a secondary coolant loop to keep the explosive refrigerant out of the passenger compartment) (Mathur 2001a, 2001b, 2003b), and ultralow-emission R-134a systems. Insufficient information exists to determine whether any one of these systems will be able to achieve the predominant position of R-134a today. Significant work has been done on carbon dioxide and hydrocarbons by OEMs and suppliers in North America, Europe, and Japan, and the Society of Automotive Engineers' (SAE) Interior Climate Control Committee has been developing multiple standards related to carbon dioxide. SAE also has held several conferences on alternative refrigerants. Vehicles with alternative refrigerant systems (CO_2 and hydrocarbons, both drop-in and with secondary loop systems) and baseline and enhanced R-134a (e.g., a suction line heat exchanger and oil separator) systems were tested for performance and comfort. Recently, Spatz (2006) proposed an alternative refrigerant, Fluid H, which has a very low global warming potential (GWP) and is non-flammable. Common polyalkylene glycol (PAG) lubricants have been used for conducting tests with this working fluid. Based on preliminary testing conducted on a vehicle, it is being proposed as a "drop-in" replacement refrigerant. Initial material compatibility evaluations did not reveal any issues.

New Vehicles. The phaseout of R-12 has led to the use of non-chlorofluorocarbon (non-CFC) alternatives in vehicles. The popular choice is R-134a because its physical and thermodynamic properties closely match those of R-12. Because its miscibility with mineral oil is poor, R-134a requires the use of synthetic lubricants such as PAG or polyol ester (POE). PAGs are currently preferred. These lubricants (especially PAGs) are more hygroscopic than mineral oil; production and service procedures must emphasize the need for system dehydration and limited exposure of the lubricants to atmospheric moisture.

Older Vehicles. Vehicles originally equipped with R-12 do not require retrofit to another refrigerant as long as an affordable supply of new or reclaimed R-12 exists. When circumstances require it, most air conditioners can be modified to use R-134a and POE. When PAG oil is used in a retrofit, the remaining mineral oil should be removed to levels established by the original equipment manufacturer to prevent residual chlorides from breaking down the PAG.

Several blends of two or more refrigerants are being sold as "drop-in" replacements for R-12. They should not be used without

a thorough investigation of their effect on performance and reliability under all operating conditions. Other concerns include (1) flammability, (2) fractionation, (3) evaporator temperature glide, (4) increased probability of adding the wrong refrigerant or oil in future service, and (5) compounded complexity of refrigerant reclaim.

European Regulation of Mobile Air Conditioning. The EU directive (Vainio 2006) states that the phaseout of HFC-134a will start on January 1, 2011, for all new models. From January 1, 2017, no new vehicles sold in the EU can use HFC-134a or any fluorinated gas with a global warming potential higher than 150. Retrofitting vehicles with HFC-134a will not be allowed after January 1, 2011. Refrigerant leakage rates for single- and dual-evaporator AC systems have been defined as less than 40 and 60 g (1.4 to 2.1 oz), respectively. Using nonrefillable containers will no longer be allowed. This directive also covers the safety of the mobile air conditioners. All fluorinated gases covered by the Kyoto protocol will be recovered.

Enhanced R-134a Systems. SAE has initiated a program to improve the performance of existing R-134a systems. The goals are to (1) identify technologies to reduce mobile air-conditioning system R-134a refrigerant leakage by 50%, (2) improve R-134a mobile air-conditioning system efficiency [coefficient of performance (COP)] by 30%, (3) reduce vehicle soak and driving heat loads by 30% over current vehicles to reduce cooling requirements, and (4) reduce refrigerant loss during service and at end of life by 50%.

Advanced Technologies

HVAC suppliers are aggressively working on advancements for mobile HVAC to reduce energy consumption and improve thermal comfort for occupants. For instance, researchers are investigating using ventilated car seats to reduce air conditioning use and improve fuel efficiency without compromising thermal comfort (Lustbader 2005). Some other important technologies are as follows; Mathur (2004b) discusses them in greater detail.

Brushless Motors. These motors, used in some newer cars, are simpler than standard motors and are more reliable. Advantages include the following: (1) motor efficiency is higher, (2) commutation is accomplished electronically, (3) very high speeds and torque are possible without arcing, (4) thermal resistance is lower and the operating temperature range is thus wider, and (5) the absence of brushes reduces maintenance requirements and eliminates brush residue contamination of bearings or the environment. Because there is no brush arcing or commutation, brushless motors are much quieter, both electrically and audibly.

Positive-Temperature-Coefficient (PTC) Heaters. PTC heaters are small, ceramic-based heaters that use less energy and less time to heat more quickly than conventional units. They self-regulate at a preset temperature by regulating resistance to vary their wattage. Thus, their greater thermal dissipation results in higher efficiency. These systems are maintenance-free and very reliable. PTC heaters could be used in the HVAC system to hasten cabin heating during cold start-ups by providing heat to occupants until the engine is warm (Hauck 2003).

Smart Engine Cooling Systems with Electric Water Pumps (EWPs). These cooling systems use both an electric and mechanical water pump, or replace the mechanical water pump with a EWP (Wagner et al. 2003). Typically, an EWP system includes a 100 to 600 W electric pump, four-way water valve (Chanfreau et al. 2003), sensor, engine control management system, software, and a variable-speed radiator fan. At cold start-ups, allowing little or no flow to the radiator hastens engine warm-up, thus reducing emissions and improving fuel economy. Because the water (or coolant) temperature is precisely maintained, thermal stresses in the engine are less. Once the engine coolant is heated, this system can provide thermal comfort, even at idle or with the engine off, by pumping coolant through the heater core and running the blower.

42 V Systems. Energy requirements of modern vehicles have increased significantly as the needs of motors, actuators, and other electrical equipment have increased. Auto manufacturers are investigating using 42 V for high-load equipment (e.g., compressors, blower, condenser fans, PTC heaters, controls), and reserving the existing 12 V grid for lighting and other smaller-load accessories. This would improve air-conditioning system performance, because compressor speed would be independent of engine speed. These systems could be used for hybrid, electric, or fuel-cell vehicles.

MASS TRANSIT

This section discusses buses, rail cars, and fixed-guideway vehicles that transport large numbers of people. The air-conditioning systems for these vehicles generally use commercial components, and packaging may be specific to the application, often integral with the external styling. Weight, envelope, and power consumption are important factors. Power sources may be electrical (ac or dc), engine shaft, compressed air, or hydraulic. These sources are often limited, variable, and interruptible. Characteristics specific to each application are discussed in the following subsections. Design aspects common to all mass-transit HVAC systems include passenger comfort (ventilation, thermal comfort, air quality, expectation) and thermal load analysis (passenger dynamic metabolic rate, solar loading, infiltration, multiple climates, vehicle velocity, and, in urban applications, rapid interior load change).

VENTILATION AND THERMAL COMFORT

The requirements of ASHRAE *Standards* 55 and 62.1 apply for transportation applications, with special considerations, because passengers in transit have different perceptions and expectations than a typical building occupant. These considerations involve length of occupancy, occupancy turnover, infiltration, outside air quality, frequency and duration of door openings, personal preference, interior contamination sources such as smoking, and exterior contamination sources such as engine exhaust.

Typically, outside air ventilation between 5 and 10 cfm per passenger (at nominal passenger load conditions) is mechanically supplied at all times, although some variable-volume systems have been applied. Design load is defined by the specification documents. It may be based on the number of seats (for long distances) or also include a number of standees (for short distances), usually about 50% of the maximum standees possible. Measurement of CO_2 for air quality control is not practical in these applications because of extremely variable background CO_2 levels. The effective ventilation rate per passenger is generally somewhat higher than the nominal mechanical supply, and varies with the type of vehicle, length of ride, door openings, and average passenger occupancy. An important consideration is emergency ventilation when other systems fail; for example, the propulsion system may strand passengers in a situation where exit is not possible. Outside air dampers may be required by the procurement specification for emergencies.

The nature of the transit service may be roughly categorized by average journey time per passenger and interval between station stops, and this service type affects the necessary interior conditions within the vehicle. For example, a commuter rail passenger may have a journey time of an hour or more, with few stops. Passengers riding such service may remove heavy outer clothing before being seated. In contrast, a subway rider typically will not remove heavy clothing during a 10 min ride. Clothing and the environment from which passengers come, including how long they were exposed to those conditions and what they were doing (e.g., waiting for the train outdoors in the winter), are important factors in transit comfort. At the opposite extreme, most subway stations are not climate controlled, and often reach dry-bulb temperatures over 100°F in the summer. Thus, when boarding a climate-controlled vehicle,

these passengers immediately perceive a significant increase in comfort. However, a passenger adjusts to a new environment in about 10 to 20 min; after that, the traditional comfort indices begin to apply, and the same interior conditions that were perceived as comfortable may now be perceived as less than comfortable. Before stabilization, a passenger may prefer higher-velocity air or cooler or warmer temperatures, depending to a certain extent on clothing. At the same time, other passengers may already have stabilized and have completely different comfort control desires. Therefore, the transit system designer is presented with a number of unusual requirements in providing comfort for all.

In addition to the effect on perceived comfort, the passenger's pre-boarding environment and activity also affect the system interior loads. Jones et al. (1994) evaluated the heat load imposed by people under transient weather and activity conditions as opposed to traditional steady-state metabolic rates. An application program, TRAN-MOD, was developed that allows a designer to predict the thermal loads imposed by passengers (Jones and He 1993). Variables are activity, clothing, wet- and dry-bulb temperatures, and precipitation.

European Committee for Standardization (CEN) *Standard* EN 13129-1 provides guidance in the area of railroad passenger comfort. Although this standard does not apply to countries outside the CEN, the information is valuable and may not be readily available elsewhere.

THERMAL LOAD ANALYSIS

Cooling Design Considerations

Thermal load analysis for transit applications differs from stationary, building-based systems because vehicle orientation and occupant density change regularly on street-level and subway vehicles and to a somewhat lesser degree on commuter and long-distance transportation. Summer operation is particularly affected because cooling load is affected more by solar and passenger heat gain than by outside air conditions. ASHRAE *Standard* 55 design parameters for occupant comfort may not always apply. Vehicle construction does not allow the low thermal conductivity levels of buildings, and fenestration material must have safety features not necessary in other applications. For these reasons, thermal loads must be calculated differently. Because main-line passenger rail cars and buses must operate in various parts of the country, the air conditioning must be designed to handle the national seasonal extreme design days. Commuter and local transit vehicles operate in a small geographical area, so only the local design ambient conditions need be considered.

The following cooling load components should be considered:

- Ambient air conditions for locations in North America and worldwide are given in Chapter 28 of the 2005 *ASHRAE Handbook—Fundamentals.* For vehicles operating in an urban area, the heat island effect should be considered if the Handbook design values are derived from remote reporting stations. For subway car operation, tunnel temperatures should be considered.
- For vehicle interior comfort conditions, consult Figure 5 in Chapter 8 of the 2005 *ASHRAE Handbook—Fundamentals.* Total heat gain from passengers depends on passenger activity before boarding the vehicle, waiting time, journey time, and whether they are standing or seated during the journey. Representative values are given in Table 1 in Chapter 30 of the 2005 *ASHRAE Handbook—Fundamentals.*
- Ventilation air loads should be calculated using the method in Chapter 30 of the 2005 *ASHRAE Handbook—Fundamentals*, in the section on Infiltration and Moisture Migration Heat Gains. Air leakage and air entering during door dwell time should be taken into account.
- Interior heat includes that produced by the evaporator fan motor, inside lighting, and electrical controls.

- The vehicle's conductivity, in Btu/h·°F, should be provided by the vehicle designers. For the outside skin temperature, use the values in Table 15 in Chapter 29 of the 1997 *ASHRAE Handbook—Fundamentals*; the car design dry bulb should be used as the interior temperature.
- The instantaneous solar gain through the glazing should be calculated using summer midafternoon values and the glass shading coefficient. The direction of travel for this period of the day should be determined before using the solar heat gain factors listed in Chapter 30 of the 2005 *ASHRAE Handbook—Fundamentals*. The glass shading coefficient must be obtained from the window supplier.

The summer cooling analysis should be completed for different times of the day and different passenger densities to verify a reliable result. Cooling equipment capacity should consider fouling and eventual deterioration of heat transfer surfaces.

Heating Design Considerations

Winter outside design conditions can be taken from Chapter 28 of the 2005 *ASHRAE Handbook—Fundamentals*. Interior temperatures can be taken from Figure 5 in Chapter 8 of the 2005 *ASHRAE Handbook—Fundamentals*. During winter, conductivity is the major heat loss. The heat required to temper ventilation air and to counteract infiltration through the body and during door openings must also be considered.

Other Considerations

Harsh environments and the incursion of dirt and dust inhibit the efficiency of HVAC units. Specifications should include precise maintenance instructions to avoid capacity loss and compromised passenger comfort.

BUS AIR CONDITIONING

In general, bus air-conditioning systems can be classified as inter-urban, urban, or small/shuttle bus systems. Bus air-conditioning design differs from other air-conditioning applications because of climatic conditions in which the bus operates, equipment size limitations, and compressor rpm. Providing a comfortable climate inside a bus passenger compartment is difficult because the occupancy rate per unit of surface and volume is high, glazed area is very large, and outside conditions are highly variable. Factors such as high ambient temperatures, dust, rain, snow, road shocks, hail, and sleet should be considered in the design. Units should operate satisfactorily in ambient conditions from –22 to 122°F.

Ambient air quality must also be considered. Air intakes are usually subjected to thermal contamination from road surfaces, condenser air recirculation, or radiator air discharge. Vehicle motion also introduces pressure variables that affect condenser fan performance. In addition, engine speed governs compressor speed, which affects compressor capacity. R-134a is the current refrigerant of choice, but some units operate with refrigerants such as R-22 or R-407C.

Bus air conditioners are initially performance-tested as units in a climate-controlled test cell. Performance tests encompass unit operation at different compressor speeds to make sure the compressor performance parameters (e.g., unit operation at maximum ambient conditions, minimum ambient condition, TXV sizing, oil return and vibration/shock) are within boundaries. In addition, individual parts that make the unit should be qualified before use. Larger test cells that can hold a bus are commonly used to verify installed unit performance. Pulldown tests previously known as the "Houston pulldown test" and the "White Book pulldown test" have been replaced by a test described in American Public Transportation Association (APTA) Standard Bus Procurement Guidelines.

Reliability and ease of maintenance are also important design considerations. All parts requiring service or regular maintenance

should be readily accessible, and repairs should be achievable within a minimum time.

Heat Load

The main parameters that must be considered in bus air-conditioning system design include

- Occupancy data (number of passengers, distance traveled, distance traveled between stops, typical permanence time)
- Dimensions and optical properties of glass
- Outside weather conditions (temperature, relative humidity, solar radiation)
- Dimensions and thermal properties of materials in bus body
- Indoor design conditions (temperature, humidity, and air velocity)

The heating or cooling load in a passenger bus may be estimated by summing the heat flux from the following loads:

- Solid walls (side panels, roof, floor)
- Glass (side, front and rear windows)
- Passengers
- Engine and ventilation (difference in enthalpy between outside and inside air)
- Evaporator fan motor

Extreme loads for both summer and winter should be calculated. The cooling load is the most difficult load to handle; the heating load is normally handled by heat recovered from the engine. An exception is that an idling engine provides marginal heat in very cold climates. Andre et al. (1994) and Jones and He (1993) describe computational models for calculating the heat load in vehicles, as well as for simulating the thermal behavior of the passenger compartment.

The following conditions can be assumed for calculating the summer heat load in an interurban vehicle similar to that shown in Figure 9:

- Capacity of 50 passengers
- Insulation thickness of 1 to 1.5 in.
- Double-pane tinted windows
- Outdoor air intake of 400 cfm
- Road speed of 65 mph
- Inside design temperatures of 60 to 80°F and 50% rh
- Ambient temperatures for location as listed in Chapter 28 of the 2005 *ASHRAE Handbook—Fundamentals*

Loads from 3.5 to 10 tons are calculated, depending on outside weather conditions and geographic location. The typical distribution of the different heat loads during a summer day at 40° north latitude is shown in Figure 10.

Air Distribution

Air-conditioning units are configured to deliver air through ducts to outlets above the windows or to act as free-blow units. In the case of free-blow units, louvers guide the air distribution inside the bus.

Interurban Buses

These buses are designed to accommodate up to 56 passengers. The air-conditioning system is usually designed to handle extreme conditions. Interurban buses produced in North America are likely to have the evaporator and heater located under the passenger compartment floor. A four- or six-cylinder reciprocating compressor, in which some cylinders are equipped with unloaders, is popular. Some interurban buses have a separate engine-driven compressor, preferably scroll, to give more constant system performance. Figure 11 shows a typical air-conditioning arrangement for an interurban bus.

Urban Buses

Urban bus heating and cooling loads are greater than those of the interurban bus. A city bus may seat up to 50 passengers and carry a
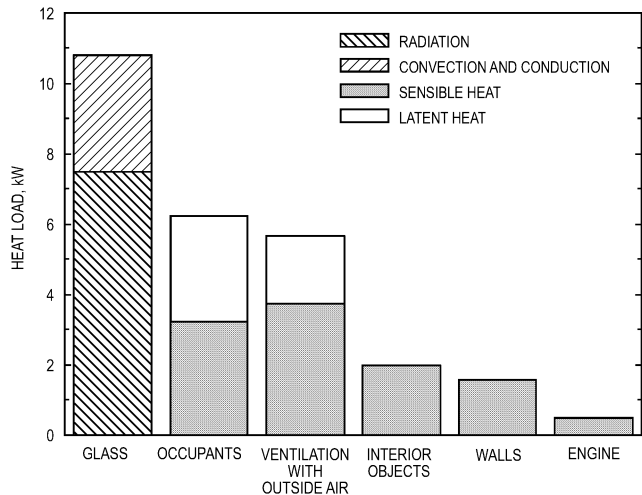
Fig. 10   Main Heat Fluxes in Bus

Fig. 9   Distribution of Heat Load (Summer)
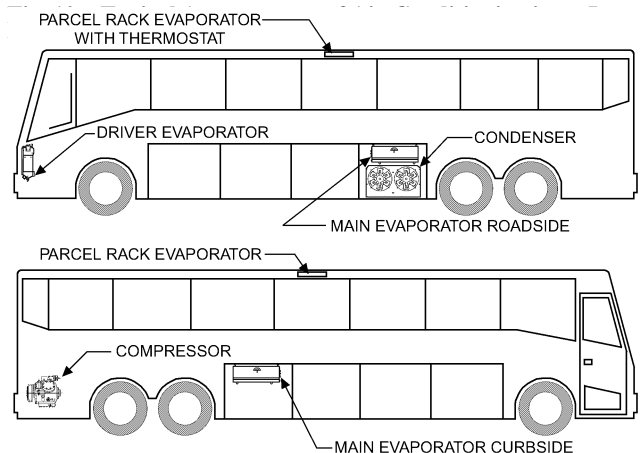
Fig. 11   Typical Arrangement of Air-Conditioning in Interurban Bus
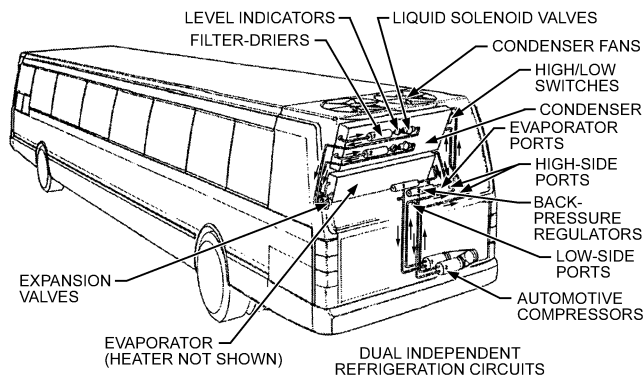
Fig. 12 Typical Mounting Location of Urban Bus Air-Conditioning Equipment

"crush load" of standing passengers. The fresh air load is greater because of the number of door openings and the infiltration around doors. Cooling capacity required for a typical 50-seat urban bus is from 6 to 10 tons. The buses are usually equipped with a roof- or rear-mounted unit, as shown in Figure 12. One or two compressors are usually belt- or shaft-driven from the propulsion engine. Capacity control is very important, because the compressor may turn more quickly than necessary at high engine speeds. Therefore, capacity control must compensate for not only the thermal load but also the engine-induced load. Cylinder unloaders are the primary means of capacity control, although evaporator pressure regulators have been use with non-unloading compressors, as shown in Figure 12. This configuration was used on buses produced between 1975 and 1995.

The heater is located just downstream of the evaporator. Hot coolant from the engine-cooling system provides sufficient heat for most operations; however, additional sources may be required in colder climates for longer idling durations. Additional floor heaters may also be required to reduce the effects of stratification. Conditioned air is delivered through overhead combination light fixture/diffuser ducts.

Low-profile rooftop-mounted units are used for either urban or interurban buses. They consist of the entire air-conditioning system except for the compressor, which is shaft- or belt-driven from the bus engine.

Small or Shuttle Buses

For small or shuttle buses such as those typically operating around airports or for schools, the evaporator is usually mounted in the rear and the condenser on the side or the roof of the bus. The evaporator unit is typically a free-blow unit.

Refrigerant Piping

Refer to Chapters 2 and 45 of the 2006 *ASHRAE Handbook—Refrigeration* for standard refrigerant piping practices. All components in the bus air-conditioning system are interconnected by copper tubing or refrigerant hose. When using copper tubing, care should be taken to analyze the effect of vibration on the tubing. Vibrational effects can be minimized by using vibration absorbers or other shock-cushioning devices. When using refrigerant hose, properties such as moisture ingression, effusion, maximum operating temperature, and burst pressure need to be taken into account. The refrigerant hose chosen should have the minimum amount of wax extractables on interaction with oil and the refrigerant.

Shock and Vibration

Most transport air-conditioning manufacturers design components for shock loading and vibrational inputs. Vibration eliminators, flexible lines, and other shock-cushioning devices interconnect

the various air-conditioning components. The vibration characteristics of each component are different; in addition, the evaporator and the condenser must undergo individual vibration and shake tests. The input levels for the shake test can be based on the worst road conditions that the bus will encounter. This input level will vary because of the weight of the unit and its mounting.

System Safety

Per the U.S. Department of Transportation, all buses with air-conditioning systems operating in North America should conform to Federal Motor Vehicle Safety *Standard* (FMVSS) 302 for flammability standards. In addition, all evaporator units inside the vehicle should be mounted away from the head impact zone, as specified by FMVSS 222.

Controls

Most buses have a simple driver control to select air conditioning or heating. In both modes, a thermal sensing element (thermistor, mercury tube, etc.) controls these systems with on/off circuitry and actuators. Many systems use solid-state control modules to interpret the bus interior and outside ambient temperatures and to generate signals to operate full or partial cooling or heating functions. In these systems, thermistor temperature sensors are used, which are usually more stable and reliable than electromechanical controls. Control systems for urban buses can also include an outside-air ventilation cycle. The percentage of fresh air intake during the ventilation cycle can vary based on individual requirements.

RAIL CAR AIR CONDITIONING

Passenger rail car air-conditioning systems are generally electromechanical, direct-expansion units. R-22, a hydrochlorofluorocarbon (HCFC), has been the refrigerant most commonly used since the phaseout for R-12. R-134a, a medium-pressure refrigerant, has been used as a retrofit refrigerant in North America on systems originally designed to operate with R-12, and is commonly used in Europe for new equipment, mainly variable-speed screw compressors that are competitive in weight to R-22 reciprocating compressors. As HCFC refrigerants are phased out, the most likely replacements are hydrofluorocarbons (HFCs). R-407C is currently favored over R-410A because of the high condensing temperatures commonly found in transit applications. R-407C does have closely similar operating characteristics to R-22 and can, in many cases, be used as a replacement with minimal system changes.

Electronic, automatic controls are common, with a trend toward microprocessor control with increasing capability for fault monitoring and logging. Electric heating elements in the air-conditioning unit or supply duct temper outdoor air brought in for ventilation and are also used to control humidity by reheating the conditioned supply air during cooling partial-load conditions.

Air-cycle technology has been tested for passenger rail car air conditioning in Germany (Giles et al. 1997); however, issues of greater weight, higher cost, and low efficiency need to be addressed before it is widely accepted. Currently, there is no known research into using carbon dioxide or other transcritical refrigerants for transit. However, it seems likely that development of these systems for automotive use may lead to their use in bus applications, with possible expansion for other modes of transit.

Vehicle Types

Main-line intercity passenger rail service generally operates single and bilevel cars hauled by a locomotive. Locomotive-driven alternators or solid-state inverters distribute power via an intercar cable power bus to air-conditioning equipment in each car. A typical rail car has a control package and two air-conditioning systems. The units are usually either split, with the compressor/condenser units located in the car undercarriage area and the evaporator-blower

portion mounted in the ceiling area, or self-contained packages mounted in interior equipment rooms. Underfloor and roof-mounted package units are less common in intercity cars.

Commuter cars used to provide passenger service from the suburbs into and around large cities are similar in size to main-line cars. Air-conditioning equipment generally consists of two evaporator-heater fan units mounted above the ceiling with a common or two separate underfloor-mounted compressor-condenser unit(s) and a control package. These cars may be locomotive hauled and have air-conditioning arrangements similar to main-line intercity cars, but they are often self propelled by high-voltage direct current (dc) or alternating current (ac) power supplied from an overhead catenary or from a dc-supplied third rail system. On such cars, the air conditioning may operate on ac or dc power. Self-propelled diesel-driven vehicles that use onboard-generated power for the air-conditioning systems still operate in a few areas.

Subway and **elevated rapid-transit cars** usually operate on a third-rail dc power supply. In the past, the air-conditioning system motors were commonly powered directly from the third-rail dc supply voltage. Most new equipment operates from three-phase ac power provided by a solid-state inverter. The inverter may be either an independent system or a component of the HVAC system. Split air-conditioning systems are common, with evaporators in the interior ceiling area and underfloor-mounted condensing sections, although unitary package units mounted on the roof or under the floor are increasingly popular.

Streetcars and **light-rail vehicles** usually run on ac or dc power transmitted via an overhead catenary wire, and have air-conditioning equipment similar to rapid-transit cars. Roof-mounted packages are used more often than undercar or split systems. This is largely because of the lack of undercar space. Figure 13 shows a typical configuration for these vehicles.

Equipment Design Considerations

Design considerations unique to transit HVAC equipment include the characteristics of the available power supply, weight limits, type of vehicle, and vehicle service parameters. Thus, ac-powered, semi-hermetic or hermetic compressors, which are lighter than open machines with dc motor drives, are a common choice. However, each car design must be examined in this respect because dc/ac inverters may increase not only the total weight, but also the total power draw, because of conversion losses.
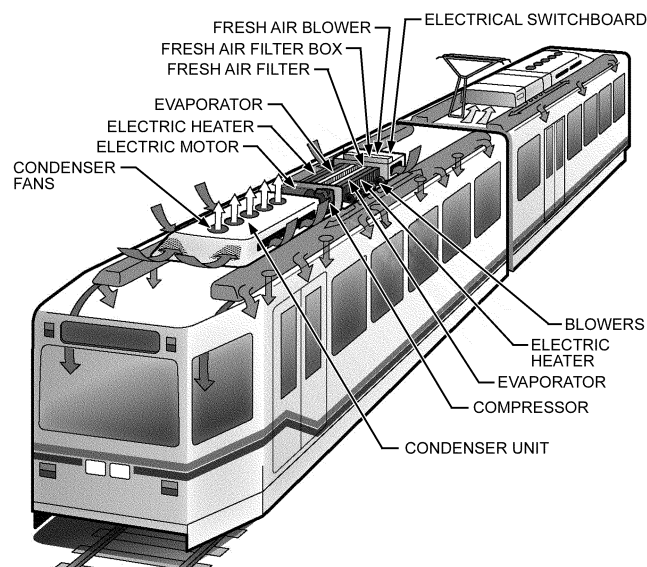
Fig. 13   Typical Light Rail Vehicle with Roof-Mounted HVAC System

Other concerns in equipment selection include the space required, location, accessibility, reliability, and maintainability. Interior and exterior equipment noise levels must be considered both during the early stages of design and later, when the equipment is coordinated with the car builder's ductwork and grilles.

Compressors. Reciprocating and vane compressors are commonly used, although scroll compressors are becoming increasingly popular. The scroll compressor is inherently more tolerant of flooded starts and liquid slugging common in the rail application than any other type of positive-displacement compressor. The low clearance volume of the scroll compressor allows it to operate at high discharge pressure more effectively than reciprocating compressors. Lower weight and less vibration and noise are benefits, as well. Screw compressors are also increasingly used (mostly in Europe), as are variable-speed compressor drives.

Power Supply Characteristics. Vehicles that draw their power from a stationary supply such as a third rail or overhead catenary wire are subject to frequent power interruptions as the train passes through gaps in the third rail or phase breaks in the overhead. These interruptions cause the HVAC equipment to shut down independently of the control system, and the design must take into account these losses of power and the subsequent need to restart the equipment. Vehicles that generate electrical power from an onboard source are less affected by power interruptions, although their capacity is limited. In either case, HVAC system control design must be coordinated with the vehicle's power supply and distribution system to avoid overloading vehicle systems during both steady-state and start-up (in-rush current) conditions. Additionally, it is desirable to prevent the vehicle's power supply from intentionally removing power from the HVAC equipment without an orderly shutdown sequence (including a pump-down cycle, if necessary).

Configuration and Space Constraints. Space underneath and inside a rail car is at a premium. Components are usually built to fit the configuration of the available space. Overall car height, roof profile, ceiling cavity, and wayside clearance restrictions often determine the shape and size of equipment.

Special Environmental Considerations. Dirt and corrosion constitute an important design factor, especially if the equipment is beneath the car floor, where it is subject to extremes of weather and severe dirt conditions. For this reason, corrosion-resistant materials and coatings must be selected. Aluminum has not proved durable in exterior exposed applications; the sandblasting effect tends to degrade any surface treatment on it. Because dirt pickup cannot be avoided, the equipment must be designed for quick and easy cleaning; access doors should be provided, and evaporator and condenser fin spacing is usually limited to 8 to 10 fins per inch. Closer spacing causes more rapid dirt build-up and higher cleaning costs. Dirt and severe environmental conditions must also be considered in selecting motors and controls.

Maintenance Provisions. Railroad HVAC equipment is subjected to mechanical shock and vibration during operation, is frequently required to operate under conditions of elevated condensing temperature and pressure, and is subjected to frequent on/off cycling because of power supply interruptions and other conditions that are not typical for a stationary application. As a consequence, the rail HVAC system's components are more highly stressed than equivalent components in a stationary system, and thus require more frequent maintenance and servicing. Because a passenger rail car with sealed windows and a well-insulated structure becomes almost unusable if the air conditioning fails, high reliability is important. Equipment design needs to consider the ease of routine service and time needed to diagnose and repair the system. The control equipment thus often incorporates monitoring and diagnostic capabilities to allow quick diagnosis and correction of a failure. However, many trains are designed with several individual vehicles permanently coupled together, in which case the failure of a single HVAC unit causes multiple cars to become unavailable for service while the

HVAC system is diagnosed and repaired. The time to diagnose and repair a system varies. Railroads, by their nature, are schedule driven, and varying, unknown repair time is incompatible with the need to provide scheduled service. Therefore, many users are moving away from fully on-car-serviceable air conditioners, and toward modular, self-contained units with hermetically sealed refrigerant systems. These units are designed for rapid removal and replacement to allow the vehicle to return to service in a short, predictable time. The faulty HVAC equipment is diagnosed and repaired off-car in a dedicated air-conditioning service area.

Safety. Security of the air-conditioning equipment attachment to the vehicle must be considered, especially on equipment located beneath the car. Vibration isolators and supports should be designed to safely retain the equipment on the vehicle, even if the vibration isolators or fasteners fail completely. A piece of equipment that dangles or drops off could cause a train derailment. All belt drives and other rotating equipment must be safety guarded. High-voltage controls and equipment must be labeled by approved warning signs. Pressure vessels and coils must meet ASME test specifications for protection of passengers and maintenance personnel. Materials selection criteria include low flammability, low toxicity, and low smoke emission.

Special Design Considerations. The design, location, and installation of air-cooled condenser sections must allow for the possibility of hot condenser discharge air recirculation into the condenser inlet (in the case of split systems), or into the outdoor air intakes (in the case of roof-mounted unitary systems), as well as the hot condenser discharge from trains on adjacent tracks that may occur at passenger loading platforms or in tunnels. To prevent a total system shutdown because of high discharge pressure, a capacity reduction control device is typically used to reduce the cooling capacity before system pressure reaches the high-pressure safety switch setting, thus temporarily reducing discharge pressure.

Even with coordination between the HVAC controls and the vehicle's power supply or distribution system, abrupt shutdown of the refrigeration system caused by power loss is common. The typical split-system arrangement places the compressor at or near the low point in the system. The combination of these factors results in undesired migration of refrigerant to the compressor during the off cycle. To reduce the likelihood of flooded compressor starts, using a suction line accumulator and crankcase heater is recommended.

Other Requirements

Most cars are equipped with both overhead and floor heat, typically provided by electric resistance elements. The control design commonly uses overhead heat to raise the temperature of the recirculated and ventilation air mixture to slightly above the car design temperature, while floor heat offsets heat loss through the car body. This arrangement is intended to limit stratification in the passenger compartment by promoting buoyant, convective air circulation. Times of maximum occupancy, outdoor ambient, and solar gain must be ascertained. The peak cooling load on urban transit cars usually coincides with the evening rush hour, and the peak load on intercity rail cars occurs in the midafternoon.

Heating capacity for the car depends on body construction, car size, and the design area-averaged relative wind-vehicle velocity. In some instances, minimum car warm-up time may be the governing factor. On long-distance trains, the toilets, galley, and lounges often have exhaust fans. Ventilation airflow must exceed forced exhaust air rates sufficiently to maintain positive car pressure. Ventilation air pressurizes the car and reduces infiltration.

Air Distribution and Ventilation

The most common air distribution system is a centerline supply duct running the length of the car between the ceiling and the roof. Air outlets are usually ceiling-mounted linear slot air diffusers.

Louvered or egg crate recirculation grilles are positioned in the ceiling beneath the evaporator units. The main supply duct must be insulated from the ceiling cavity to prevent thermal gain/loss and condensation. Taking ventilation air from both sides of the roof line helps overcome the effect of wind. Adequate snow and rain louvers and, in some cases, internal baffles, must be installed on the outdoor air intakes. Separate outdoor air filters are usually combined with either a return or mixed air filter. Disposable media or permanent, cleanable air filters are used and are usually serviced every month. Some long-haul cars, such as sleeper cars, require a network of delivered-air and return ducts. Duct design should consider noise and static pressure losses.

Piping Design

Standard refrigerant piping practice is followed. Pipe joints should be accessible for inspection and, on split systems, not concealed in car walls. Evacuation, leak testing, and dehydration must be completed successfully after installation and before charging. Piping should be supported adequately and installed without traps that could retard the flow of lubricant back to the compressor. Pipe sizing and arrangement should be in accordance with Chapter 2 of the 2006 *ASHRAE Handbook—Refrigeration*. Evacuation, dehydration, and charging should be performed as described in Chapter 45 of that volume. Piping on packaged units should also conform to these recommendations.

Control Requirements

Rail HVAC control systems typically automatically transition between cooling and heating operation, based on interior and exterior dry-bulb temperature. The cooling and heating set points are generally different. This difference provides a control dead band to prevent the system from cycling directly between cooling and heating, and accommodates passengers' seasonal clothing. System capacity is matched to part-load conditions with some combination of evaporator coil staging, evaporator fan speed control, compressor cylinder unloading, or variable-speed compressor control in cooling mode, and staging or duty cycling of heat in heating mode. The control system typically does not consider latent heat information in the control algorithm, although reheat is commonly used to increase the apparent interior sensible load as the interior dry-bulb temperature falls below the desired cooling set point, to maintain humidity removal. Unitary systems may use hot-gas bypass for this purpose rather than electric reheat. If the interior dry-bulb temperature falls below the desired cooling set point, even with capacity reduction and reheat, the refrigeration system will shut down and the HVAC system will provide ventilation only. If the interior temperature drops to the heating set point, the system transitions to heating mode. Before the development of analog electronic or microprocessor control systems, this dry-bulb based control algorithm was implemented by banks of thermostats. This arrangement resulted in multiple, load-dependent interior set points as the system established quasi-equilibrium conditions within the dead band of each individual thermostat. When analog electronic controls were introduced in the early 1980s, they emulated this thermostat-based control algorithm, which is still often followed today in North America. Recently, several European and Asian HVAC manufacturers have introduced proportional-integral-derivative (PID) control systems, common in those markets for several years, to the North American market. Higher energy costs and greater environmental concern in Europe and Asia have led some manufacturers to include energy conservation algorithms in controls intended for use in those markets. The availability of robust, low-cost humidity sensors may lead to the use of latent heat information in control algorithms.

A pumpdown cycle and low-ambient lockout are recommended on split systems to protect the compressor from damage caused by liquid flooding the compressor and subsequent flooded starts. In

addition, the compressor may be fitted with a crankcase heater that is energized during the compressor off cycle.

FIXED-GUIDEWAY VEHICLE AIR CONDITIONING

Fixed-guideway (FGW) systems, commonly called people movers, can be monorails or rubber-tired cars running on an elevated or grade-level guideway, as seen at airports and in urban areas. The guideway directs and steers the vehicle and provides electrical power to operate the car's traction motors (in some cases, the vehicle is propelled by a metal cable, driven by a motor mounted at the end of the guideway), lighting, electronics, air conditioner, and heater. People movers are usually unmanned and computer-controlled from a central point. Operations control determines vehicle speed, headway, and the length of time doors stay open, based on telemetry from individual cars or trains. Therefore, reliable and effective environmental control is essential.

People movers are usually smaller than most other mass-transit vehicles, generally having spaces for 8 to 40 seated passengers and generous floor space for standing passengers. Under some conditions of passenger loading, a 40 ft car can accommodate 100 passengers. The wide range of passenger loading and solar exposure make it essential that the car's air conditioner be especially responsive to the amount of cooling required at a given moment.

System Types

The HVAC for a people mover is usually one of three types:

- Conventional undercar condensing unit and compressor unit (which includes control box) connected with refrigerant piping to an evaporator/blower unit mounted above the car ceiling
- Packaged, roof-mounted unit having all components in one enclosure and mated to an air distribution system built into the car ceiling
- Packaged, undercar-mounted unit mated to supply and return air ducts built into the car body

Some vehicles are equipped with two systems, one at each end; each system provides one-half of the maximum cooling requirement. U.S. systems usually operate on the guideway's power supply of 460 to 600 V (ac), 60 Hz. Some newer systems with dc track power operate on 240 V (ac), 60 Hz from an inverter. Figures 14 and 15 show some arrangements used with fixed-guideway people mover vehicles, although similar arrangements could also apply to rail.

Refrigeration Components

Because commercial electrical power is available, standard semihermetic motor-compressors and commercially available fan motors and other components can be used. Compressors generally

have one or two stages of unloaders, and/or hot-gas bypass is used to maintain cooling at low loads. Condenser and evaporator coils are copper tube with copper or aluminum fins. Generally, flat fins are preferred for undercar condensers to make it simpler to clean the coils. Evaporator/blower sections must often be designed for the specific vehicle and fitted to its ceiling contours. Condensing units must also be arranged to fit in the limited space available and still ensure good airflow across the condenser coil. R-22 is commonly used in these systems, although some newer systems use R-407C to meet environmental standards (zero ozone depletion potential).

Heating

Where heating must be provided, electric resistance heaters that operate on the guideway power supply are installed at the evaporator unit discharge. One or two stages of heat control are used, depending on the size of the heaters.

Controls

A solid-state control is usually used to maintain interior conditions. The cooling set point is typically between 74 and 76°F. For heating, the set point is 68°F or lower. Some controls provide humidity control by using electric heat. Between the cooling and heating set points, blowers continue to operate on a ventilation cycle. On rare occasions, two-speed blower motors are used,
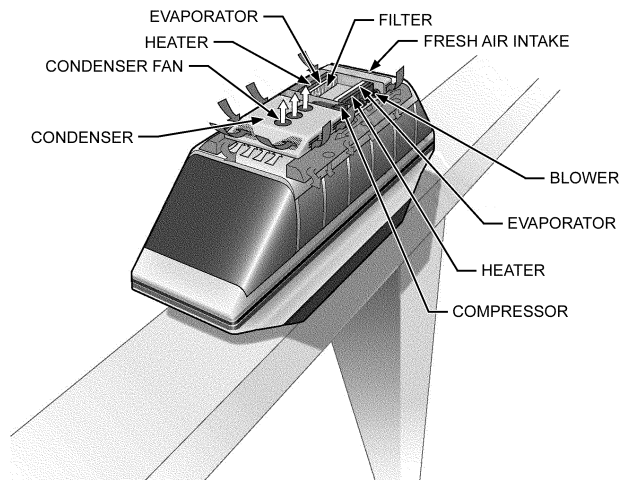
Fig. 14   Typical Small Fixed-Guideway Vehicle with Roof-Mounted HVAC System
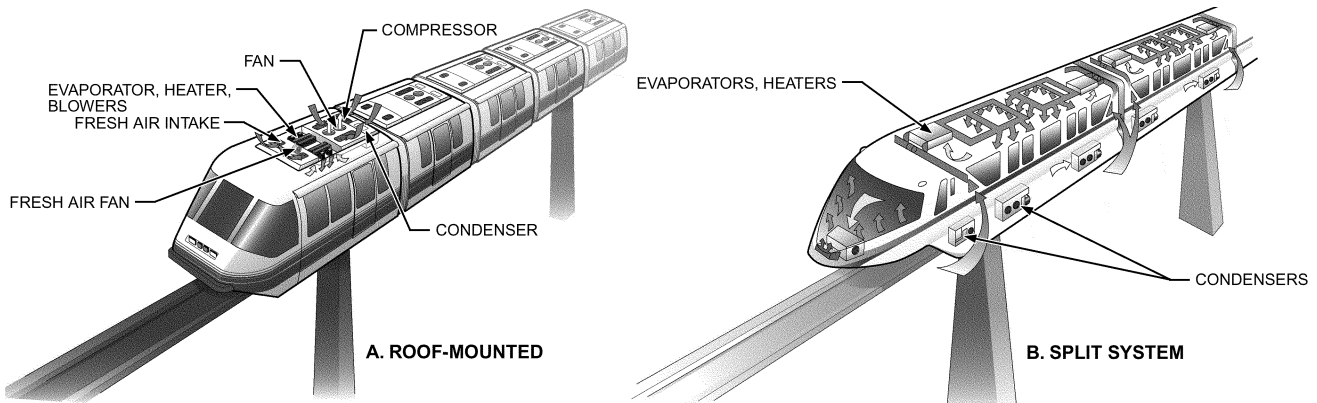
Fig. 15   Example Monorail HVAC System Configurations

switching to low speed for the heating cycle. Some controls have internal diagnostic capability and can signal the operations center when a cooling or heating malfunction occurs.

Ventilation

With overhead air-handling equipment, outside air is introduced into the return airstream at the evaporator entrance. Outside air is usually taken from a grilled or louvered opening in the end or side of the car. Depending on the configuration of components, fresh air is filtered separately or directed so that the return air filter can handle both airstreams. For undercar systems, a similar procedure is used, except air is introduced into the system through an intake in the undercar enclosure. In some cases, a separate fan is used to induce outside air into the system.

The amount of mechanical outdoor air ventilation is usually expressed as cfm per passenger on a full-load continuous basis. Passenger loading is not continuous at full load in this application, with the net result that more outside air is provided than indicated. The passengers may load and unload in groups, which causes additional air exchange with the outside. Frequent opening of doors, sometimes on both sides at once, allows additional natural ventilation. The effective outside air ventilation per passenger is a summation of all these factors. Some older vehicles currently in service have no mechanical outside air supply. Newer vehicles have up to 9 cfm per passenger. Lower values of mechanical ventilation, typically 5 cfm or less per passenger, are associated with travel times of less than 2 min and large passenger turnover. Longer rides justify higher rates of mechanical ventilation.

Air Distribution

With overhead equipment, air is distributed through linear ceiling diffusers that are often constructed as a part of the overhead lighting fixtures. Undercar equipment usually makes use of the void spaces in the sidewalls and below fixed seating. In all cases, the spaces used for air supply must be adequately insulated to prevent condensation on surfaces and, in the case of voids below seating, to avoid cold seating surfaces. The supply air discharge from undercar systems is typically through a windowsill diffuser. Recirculation air from overhead equipment flows through ceiling-mounted grilles. For undercar systems, return air grilles are usually found in the door wells or beneath seats.

Because of the vehicle's typical small size and low ceilings, care must be taken to design the air supply so that it does not blow directly on passengers' heads or shoulders. High rates of diffusion are needed, and diffuser placement and arrangement should cause the discharge to hug the ceiling and walls of the car. Total air quantity and discharge temperature must be carefully calculated to provide passenger comfort.

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CHAPTER 10

AIRCRAFT

ENVIRONMENTAL control system (ECS) is a generic term used in the aircraft industry for the systems and equipment associated with ventilation, heating, cooling, humidity/contamination control, and pressurization in the occupied compartments, cargo compartments, and electronic equipment bays. The term ECS often encompasses other functions such as windshield defog, airfoil anti-ice, oxygen systems, and other pneumatic demands. The regulatory or design requirements of these related functions are not covered in this chapter.

Environmental control systems of various types and complexity are used in military and civil airplane, helicopter, and spacecraft applications. This chapter applies to commercial transport aircraft that predominantly use air-cycle air conditioning for the ECS.

Commercial users categorize their ECS equipment in accordance with the Air Transport Association of America (ATAA) *Specification* No. 100, Specification for Manufacturers' Technical Data. The following ATAA 100 chapters define ECS functions and components:

- **Chapter 21**, Air Conditioning, includes heating, cooling, moisture/contaminant control, temperature control, distribution, and cabin pressure control. Common system names are the air-conditioning system (ACS) and the cabin pressure control system (CPCS).
- **Chapter 30**, Ice and Rain Protection, includes airfoil ice protection; engine cowl ice protection; and windshield ice, frost, or rain protection.
- **Chapter 35**, Oxygen, includes components that store, regulate, and deliver oxygen to the passengers and crew.
- **Chapter 36**, Pneumatic, covers ducts and components that deliver compressed air (bleed air) from a power source (main engine or auxiliary power unit) to connecting points for the using systems (Chapters 21, 30, and Chapter 80, Starting). The pneumatic system is also commonly called the engine bleed air system (EBAS).

REGULATIONS

The Federal Aviation Administration (FAA) regulates the design of transport category aircraft for operation in the United States under Federal Aviation Regulations (FAR) Part 25. ECS equipment and systems must meet these requirements, which are primarily related to health and safety of the occupants. Certification and operation of these aircraft in the United States is regulated by the FAA in FAR Part 121. Similar regulations are applied to European nations by the European Joint Aviation Authorities (JAA), which represents the combined requirements of the airworthiness authorities of the participating nations; the equivalent design regulation is JAR Part 25. Operating rules based on FAA or JAA regulations are applied individually by the nation of registry. Regulatory agencies may impose special conditions on the design, and compliance is mandatory.

Several FAR and JAR Part 25 paragraphs apply directly to transport category aircraft ECSs; those most germane to the ECS design requirements are as follows:

FAR/JAR 25.831	Ventilation
FAR 25.832	Cabin ozone concentration
FAR/JAR 25.841	Pressurized cabins
FAR/JAR 25.1309	Equipment, systems, and installations
FAR/JAR 25.1438	Pressurization and pneumatic systems
FAR/JAR 25.1461	Equipment containing high energy rotors

These regulatory requirements are summarized in the following sections; however, the applicable FAR and JAR paragraphs, amendments, and advisory circulars should be consulted for the latest revisions and full extent of the rules.

Ventilation

FAR/JAR *Paragraph* 25.831:

- Each passenger and crew compartment must be ventilated.
- Each crew member must have enough fresh air to perform their duties without undue fatigue or discomfort (minimum of 10 cfm).
- Crew and passenger compartment air must be free from hazardous concentration of gases and vapors:

  - Carbon monoxide limit is 1 part in 20,000 parts of air
  - Carbon dioxide limit is 0.5% by volume, sea level equivalent
  - Conditions must be met after reasonably probable failures

- Smoke evacuation from the cockpit must be readily accomplished without depressurization.
- The occupants of the flight deck, crew rest area, and other areas must be able to control the temperature and quantity of ventilating air to their compartments independently.

FAR *Amendment* No. 25-87:

- Under normal operating conditions and in the event of any probable failure, the ventilation system must be designed to provide each occupant with airflow containing at least 0.55 lb of fresh air per minute (or about 10 cfm at 8000 ft).
- The maximum exposure at any given temperature is specified as a function of the temperature exposure.

JAR ACJ (*Advisory Circular-Joint*) 25.831:

- The supply of fresh air in the event of loss of one source should not be less than 0.4 lb/min per person for any period exceeding 5 min. However, reductions below this flow rate may be accepted provided that the compartment environment can be maintained at a level that is not hazardous to the occupant.
- Where the air supply is supplemented by a recirculating system, it should be possible to stop the recirculating system.

Cabin Ozone Concentration

FAR 25.832 specifies the cabin ozone concentration during flight must be shown not to exceed

The preparation of this chapter is assigned to TC 9.3, Transportation Air Conditioning.

- 0.25 ppm by volume, sea level equivalent, at any time above flight level 320 (32,000 ft)
- 0.10 ppm by volume, sea level equivalent, time-weighted average during any 3 h interval above flight level 270 (27,000 ft)

At present, JAR 25 has no requirement for cabin ozone concentration.

Pressurized Cabins
FAR/JAR 25.841:

- Limits the maximum cabin pressure altitude to 8000 ft at the maximum aircraft operating altitude under normal operating conditions.
- For operation above 25,000 ft, a cabin pressure altitude of not more than 15,000 ft must be maintained in the event of any reasonably probable failure or malfunction in the pressurization system.
- The makeup of cabin pressure control components, instruments, and warning indication is specified to ensure the necessary redundancy and flight crew information.

FAR *Amendment* No. 25-87 imposes additional rules for high-altitude operation.

Equipment, Systems, and Installations
FAR/JAR 25.1309:

- Systems and associated components must be designed such that occurrence of any failure that would prevent continued safe flight and landing is extremely improbable.
- The occurrence of any other failure that reduces the capability of the aircraft or the ability of the crew to cope with adverse operating conditions is improbable.
- Warning information must be provided to alert the crew to unsafe system operating conditions to enable them to take corrective action.
- Analysis in compliance with these requirements must consider possible failure modes, probability of multiple failures, undetected failures, current operating condition, crew warning, and fault detection.

FAR *Advisory Circular* AC 25.1309-1A and JAR ACJ No. 1 to JAR 25.1309 define the required failure probabilities for the various failure classifications: probable, improbable, and extremely improbable for the FAR requirements; and frequent, reasonably probable, remote, and extremely remote for the JAR requirements.

Pressurization and Pneumatic Systems

FAR 25.1438 specifies the proof and burst pressure factors for pressurization and pneumatic systems as follows:

- Pressurization system elements (air conditioning)

  - Burst pressure: 2.0 times maximum normal pressure
  - Proof pressure: 1.5 times max normal pressure

- Pneumatic system elements (bleed)

  - Burst pressure: 3.0 times maximum normal pressure
  - Proof pressure: 1.5 times maximum normal pressure

JAR 25.1438 and ACJ 25.1438 specify the proof and burst pressure factors for pressurization and pneumatic systems as follows:

- Proof pressure

  - 1.5 times worst normal operation
  - 1.33 times worst reasonable probable failure
  - 1.0 times worst remote failure

- Burst pressure

  - 3.0 times worst normal operation
  - 2.66 times worst reasonably probable failure
  - 2.0 times worst remote failure
  - 1.0 times worst extremely remote failure

Equipment Containing High-Energy Rotors
FAR/JAR 25.1461:

Equipment must comply with at least one of the following three requirements:

- High-energy rotors contained in equipment must be able to withstand damage caused by malfunctions, vibration, and abnormal temperatures.

  - Auxiliary rotor cases must be able to contain damage caused by high-energy rotor blades.
  - Equipment control devices must reasonably ensure that no operating limitations affecting the integrity of high-energy rotors will be exceeded in service.

- Testing must show that equipment containing high-energy rotors can contain any failure that occurs at the highest speed attainable with normal speed control devices inoperative.
- Equipment containing high-energy rotors must be located where rotor failure will neither endanger the occupants nor adversely affect continued safe flight.

DESIGN CONDITIONS

Design conditions for aircraft applications differ in several ways from other HVAC applications. Commercial transport aircraft operate in a physical environment that is not survivable by unprotected humans. This requires a complex ECS to provide passengers and crew with safety and comfort without health risks.

Aircraft ECSs operate under unique conditions. Outside air at altitude is extremely cold, dry, and can contain high levels of ozone. On the ground outside air can be hot, humid, and contain many pollutants such as particulate matter, aerosols, and hydrocarbons. These ambient conditions change quickly from ground operations to flight. The hot-day, high-humidity ground condition usually dictates the size of air-conditioning equipment, and high-altitude flight conditions determine the impedance necessary to overcome in order to provide adequate ventilation and pressurization bleed airflow. Maximum heating requirements can be determined by either cold-day ground or flight operations.

In addition to essential safety requirements, the ECS should provide a comfortable environment for the passengers and crew. This presents a unique challenge because of the high-density seating of the passengers and the changes in cabin pressure and the outside environment during flight. Also, aircraft systems must be lightweight, accessible for quick inspection and servicing, highly reliable, tolerant of a wide range of environmental conditions, able to withstand aircraft vibratory and maneuver loads, and able to accommodate failures occurring during flight.

Ambient Temperature, Humidity, and Pressure

Figure 1 shows typical design ambient temperature profiles for hot, standard, and cold days. The ambient temperatures used for the design of a particular aircraft may be higher or lower than those shown in Figure 1, depending on the regions in which the aircraft is to be operated. The design ambient moisture content at various altitudes that is recommended for commercial aircraft is shown in Figure 2. However, operation at moisture levels exceeding 200 grains per pound of dry air is possible in some regions. The variation in ambient pressure with altitude is shown in Figure 3.
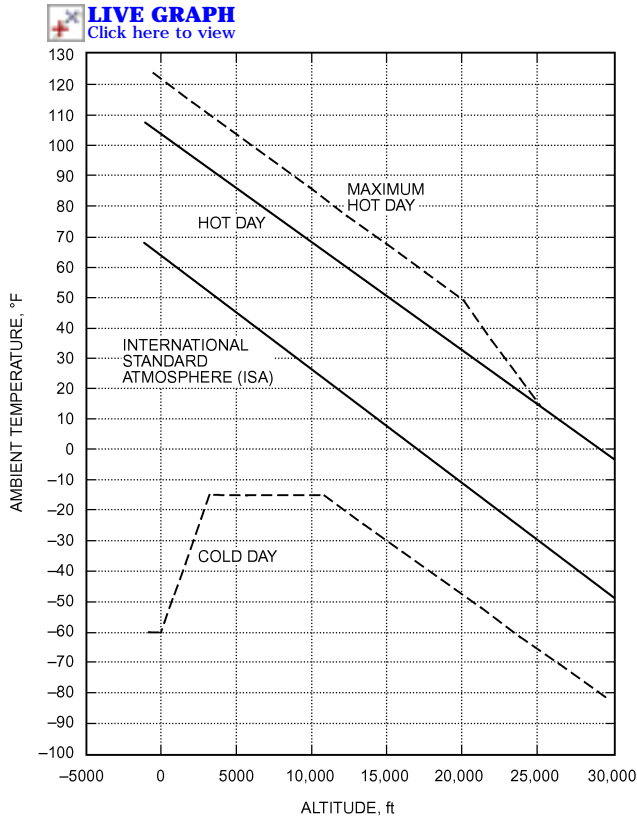
Fig. 1 Typical Ambient Temperature Profiles
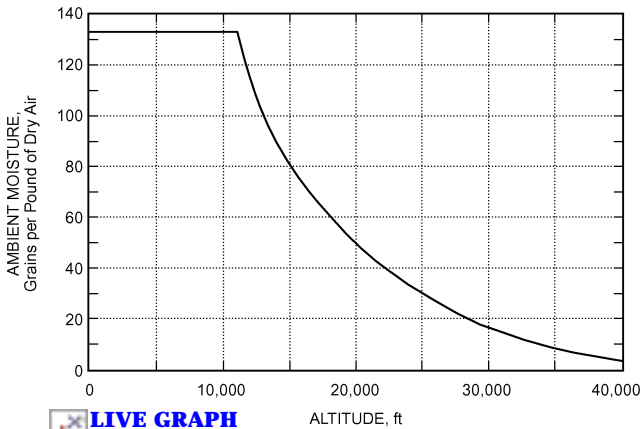
Fig. 2 Design Moisture for Equipment Performance

ECS Performance

The ECS is designed to provide a comfortable cabin temperature, acceptable ventilation, good airflow distribution across the cabin width, and sufficient bleed airflow to maintain cabin pressurization and repressurization during descent, while accounting for certain failure conditions. The ECS also includes provisions to dehumidify the cabin supply during cooling operations.

Load Determination. The steady-state cooling and heating loads for a particular aircraft model are determined by a heat transfer study of the several elements that comprise the air-conditioning load. The heat transfer involves the following factors:

- Convection between the boundary layer and the outer aircraft skin
- Radiation between the outer aircraft skin and the external environment
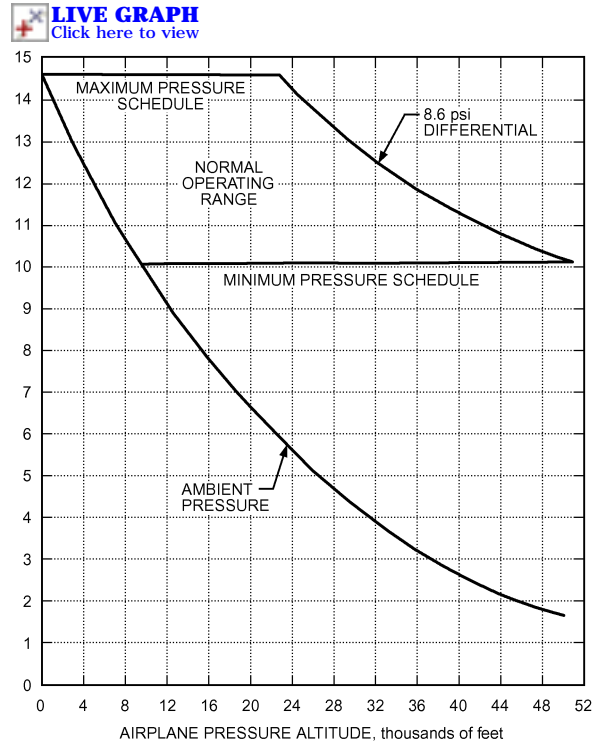
Fig. 3 Variation of Ambient Pressure with Altitude

- Solar radiation through transparent areas
- Conduction through cabin walls and the aircraft structure
- Convection between the interior cabin surface and cabin air
- Convection between the cabin air and occupants or equipment
- Convection and radiation from internal sources of heat such as electrical equipment

The heat transfer analysis should include all possible flow paths through the complex aircraft structure. Air film coefficients vary with altitude and should be considered. During flight, the increase in air temperature and pressure due to ram effects is appreciable and may be calculated from the following equations:

$$\Delta t_r = 0.2M^2 T_a F_r$$

$$\Delta p_r = (1 + 0.2M^2)^{3.5} p_a - p_a$$

where

F_r = recovery factor, dimensionless
Δt_r = increase in temperature due to ram effect, °F
M = Mach number, dimensionless
T_a = absolute static temperature of ambient air, °R
Δp_r = increase in pressure due to ram effect, psi
p_a = absolute static pressure of ambient air, psi

The average increase in aircraft skin temperature for subsonic flight is generally based on a recovery factor F_r of 0.9.

Ground and flight requirements may be quite different. For an aircraft sitting on the ground in bright sunlight, surfaces that have high absorptivity and are perpendicular to the sun's rays may have much higher temperatures than ambient. This skin temperature is reduced considerably if a breeze blows across the aircraft. Other considerations for ground operations include cooldown or warm-up requirements, and the time that doors are open for passenger and galley servicing.

Cooling. The sizing criteria for the air conditioning are usually ground operation on a hot, humid day with the aircraft fully loaded and the doors closed. A second consideration is cooldown of a

empty, heat-soaked aircraft prior to passenger loading; a cooldown time of less than 30 minutes is usually specified. A cabin temperature of between 75 and 80°F is usually specified for these hot day ground design conditions. During cruise, the system should maintain a cabin temperature of 75°F with a full passenger load.

Heating. Heating requirements are based on a partially loaded aircraft on a very cold day; cabin temperature warm-up within 30 minutes for a cold-soaked aircraft is also considered. A cabin temperature of 70°F is usually specified for these cold day ground operating conditions. During cruise, the system should maintain a cabin temperature of 75°F with a 20% passenger load, a cargo compartment temperature above 40°F, and cargo floor temperatures above 32°F to prevent the freezing of cargo.

Temperature Control. Commercial aircraft (over 19 passengers) can have as few as two zones (cockpit and cabin) and as many as seven. These crew and passenger zones are individually temperature controlled to a crew-selected temperature for each zone ranging from 65 to 85°F. Some systems have limited authority bias selectors in the passenger zones that can be adjusted by the flight attendants. The selected zone temperature is controlled to within 2°F and the temperature uniformity within the zone should be within 5°F. Separate temperature controls can be provided for cargo compartments.

Ventilation. Aircraft cabin ventilation systems can use all bleed air or a mixture of bleed and recirculated air. The bleed air source is engine compressor air that powers the air-cycle air-conditioning equipment and pressurizes the aircraft cabin. A typical ventilation system supplies 10 cfm of bleed air per occupant, which satisfies regulatory (FAA/JAA) requirements for ventilation and concentrations of carbon monoxide and carbon dioxide.

An equal amount of filtered, recirculated cabin air can be provided for improved distribution and circulation. The use of filtered, recirculated air reduces the bleed air penalty and increases cabin humidity. Most systems have no filtration of the engine bleed air supply, although bleed air centrifugal cleaners are sometimes offered as optional equipment. Some aircraft that fly where high ambient ozone levels can be expected require catalytic ozone converters.

Particulate filters are used to filter the recirculated cabin air. High-efficiency particulate air (HEPA) filters are preferred. Charcoal filters are sometimes offered as optional equipment, and are installed in series with the particulate filters. The demand for charcoal filters is low for domestic carriers because of the smoking ban on domestic

flights. Their use worldwide is also limited by cost, frequency of maintenance (replacement), and disposal requirements.

Pressurization. Cabin pressurization achieves the required partial pressures of oxygen for the crew and passengers during high-altitude flight. While the aircraft operates at altitudes above 40,000 ft, the occupied cabin must be pressurized to an equivalent altitude of 8000 ft or less to permit normal physiological functions without supplemental oxygen. The maximum pressure difference between the cabin and the outside environment is limited by aircraft structural design limits. The differential pressure control provides a cabin pressure based on the flight altitude of the aircraft. A typical cabin altitude schedule is shown in Figure 4. The cabin pressure control must also limit the normal maximum rates of change of cabin pressure; the recommended limits are 500 fpm for increasing altitude (ascent) and 300 fpm for decreasing altitude (descent). Provisions separate from the normal cabin pressure controls must be provided for positive and negative pressure relief to protect the aircraft structure.

SYSTEM DESCRIPTION

The outside air supplied to the airplane cabin is provided by the engine compressors (or auxiliary power unit in the aircraft tailcone), cooled by **air-conditioning packs** located under the wing center section, and mixed with an equal quantity of filtered, recirculated air. An air-conditioning pack uses the compressed outside air passing through it and into the airplane as the refrigerant in an air-cycle refrigeration cycle.

Air is supplied and exhausted from the cabin on a continuous basis. As shown in Figure 5, air enters the passenger cabin from overhead distribution outlets that run the length of the cabin. The exhaust air leaves the cabin through return air grilles located in the sidewalls near the floor, and running the length of the cabin on both sides. The exhaust air is continuously extracted from below the cabin floor by recirculation fans that return part of the air to the distribution system and to an outflow valve that purges the remaining exhaust air overboard. The cabin ventilation system is designed and balanced so that air supplied at one seat row leaves at approximately the same seat row, thus minimizing airflow in the fore and aft directions.

The following basic systems comprise the typical aircraft ECS.

Pneumatic System

The pneumatic system or engine bleed air system extracts a small amount of the gas turbine engine compressor air to ventilate and pressurize the aircraft compartments. A schematic of a typical

LIVE GRAPH
Click here to view

Fig. 4   Typical Cabin Altitude Schedule
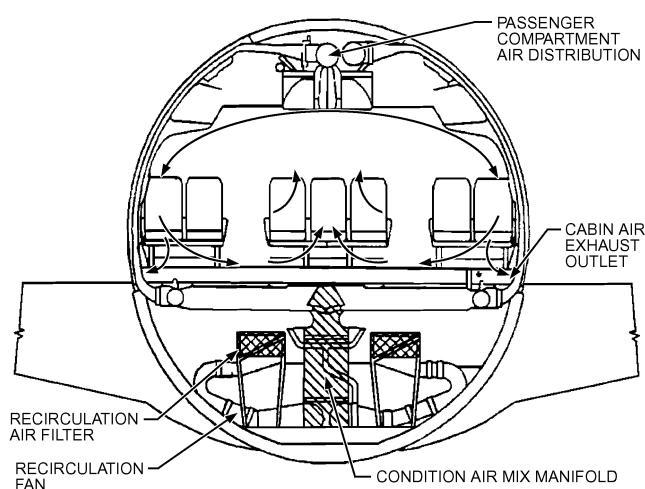
Fig. 5   Cabin Airflow Patterns
(Hunt et al. 1995)
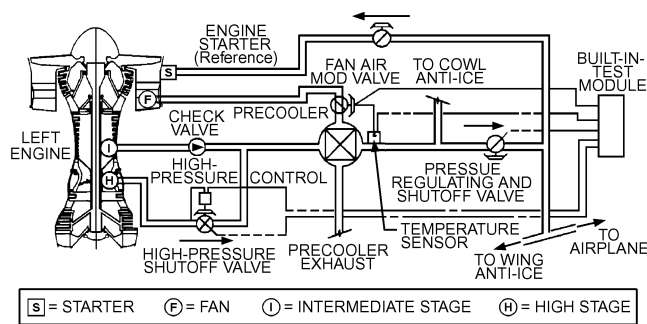
Fig. 6 Typical Engine Bleed Air System Schematic
(Hunt et al. 1995)

engine bleed air system is shown in Figure 6. During climb and cruise the bleed air is usually taken from the midstage engine bleed port for minimum bleed penalty. During idle descent it is taken from the high-stage engine bleed port where maximum available pressure is required to maintain cabin pressure and ventilation. The bleed air is pressure controlled to meet the requirements of the using system, and is usually cooled to limit bleed manifold temperatures to be compatible with fuel safety requirements. In fan jets, the fan air is used as the heat sink for the bleed air heat exchanger (precooler); for turboprop engines, ram air is used, which usually requires an ejector or fan for static operation. Other components include bleed-shutoff and modulating valves, fan-air modulating valve, sensors, controllers, and ozone converters. The pneumatic system is also used intermittently for airfoil and engine cowl anti-icing, engine start, and several other pneumatic functions.

Each engine has an identical bleed air system for redundancy and to equalize the compressor air bled from the engines. The equipment is sized to provide the necessary temperature and airflow for airfoil and cowl anti-icing, or cabin pressurization and air conditioning with one system or engine inoperative. The bleed air used for airfoil anti-icing is controlled by valves feeding piccolo tubes extending along the wing leading edge. Similar arrangements are used for anti-icing the engine cowl and tail section.

Air Conditioning

Air-cycle refrigeration is the predominant means of air conditioning for commercial and military aircraft. The reverse-Brayton cycle or Brayton refrigeration cycle is used, as opposed to the Brayton power cycle that is used in gas turbine engines. The difference between the two cycles is that in the power cycle fuel in a combustion chamber adds heat, and in the refrigeration cycle a ram-air heat exchanger removes heat. The familiar Rankine vapor cycle, which is used in building and automotive air conditioning and in domestic and commercial refrigeration, has limited use for aircraft air conditioning. The Rankine cycle is used mostly in unpressurized helicopters and general aviation applications.

In an air cycle, compression of the ambient air by the gas turbine engine compressor provides the power input. The heat of compression is removed in a heat exchanger using ambient air as the heat sink. This cooled air is refrigerated by expansion across a turbine powered by the compressed bleed air. The turbine energy resulting from the isentropic expansion is absorbed by a second rotor, which is either a ram air fan, bleed air compressor, or both. This assembly is called an **air-cycle machine** (ACM). Moisture condensed during the refrigeration process is removed by a water separator.

The compartment supply temperature is controlled by mixing hot bleed air with the refrigerated air to satisfy the range of heating and cooling. Other, more sophisticated means of temperature control are often used, such as ram air modulation, various bypass schemes in the air-conditioning pack, and downstream controls that add heat for individual zone temperature control.
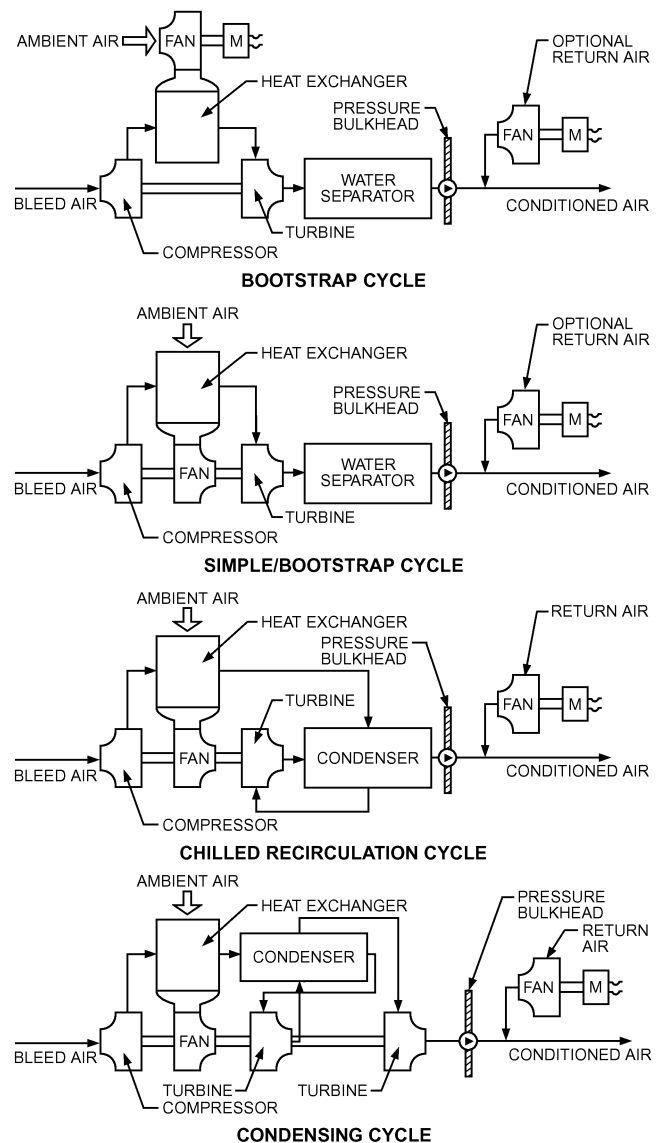
Fig. 7 Air-Conditioning Air-Cycle Configurations

The bleed airflow is controlled by a flow-control or pressure-regulating valve at the inlet of the air-conditioning pack. This valve controls bleed air used to minimize engine bleed penalties while satisfying the aircraft outside air ventilation requirements.

Most aircraft use two or three air-cycle packs operating in parallel to compensate for failures during flight and to allow the aircraft to be dispatched with certain failures. However, many business and commuter aircraft use a single-pack air conditioner; high-altitude aircraft that have single packs also have emergency pressurization equipment that uses precooled bleed air.

The most common types of air-conditioning cycles in use on commercial transport aircraft are shown in Figure 7. All equipment in common use on commercial and military aircraft is open loop, although many commercial aircraft systems include various means of recirculating cabin air to minimize engine bleed air use without sacrificing cabin comfort. The basic differences between the systems are the type of air-cycle machine used and its means of water separation.

The most common air-cycle machines in use are the bootstrap ACM, consisting of a turbine and compressor; the three-wheel ACM, consisting of a turbine, compressor, and fan; and the four-

wheel ACM, consisting of a two turbines, a compressor, and a fan. The bootstrap ACM is most commonly used for military applications, although many older commercial aircraft models use the bootstrap cycle. The three-wheel ACM (simple bootstrap cycle) is used on most of the newer commercial aircraft, including commuter aircraft and business aircraft. The four-wheel ACM (condensing cycle) is also in use in newer entries in the commercial fleet.

Both low- and high-pressure water separation are used. A **low-pressure water separator**, located downstream from the cooling turbine, has a coalescer cloth that agglomerates fine water particles entrained in the turbine discharge air into droplets. The droplets are collected, drained, and sprayed into the ram airstream using a bleed-air-powered ejector; this process increases pack cooling capacity by depressing the ram-air heat-sink temperature.

The **high-pressure water separator** condenses and removes moisture at high pressure upstream of the cooling turbine. A heat exchanger uses turbine discharge air to cool the high-pressure air sufficiently to condense most of the moisture present in the bleed air supply. The moisture is collected and sprayed into the ram airstream.

In the condensing cycle one turbine removes the high-pressure water and the second turbine does the final expansion to subfreezing-temperature air that is to be mixed with filtered, recirculated cabin air. Separating these functions recovers the heat of condensation, which results in a higher cycle efficiency. It also eliminates condenser freezing problems because the condensing heat exchanger is operated above freezing conditions.

The air-conditioning packs are located in unpressurized areas of the aircraft to minimize structural requirements of the ram air circuit that provides the necessary heat sink for the air-conditioning cycle. This location also provides protection against cabin depressurization in the event of a bleed or ram air duct rupture. The most common areas for the air-conditioning packs are the underwing/wheel well area and the tailcone area aft of the rear pressure bulkhead. Other areas include the areas adjacent to the nose wheel and overwing fairing. The temperature control components and recirculating fans are located throughout the distribution system in the pressurized compartments. The electronic pack and zone temperature controllers are located in the electrical/electronics (E/E) bay. The air-conditioning control panel is located in the flight deck. A schematic diagram of a typical air-conditioning system is shown in Figure 8.

Cabin Pressure Control

Cabin pressure is controlled by modulating the airflow discharged from the pressurized cabin through one or more cabin outflow valves. The cabin pressure control includes the outflow valves,
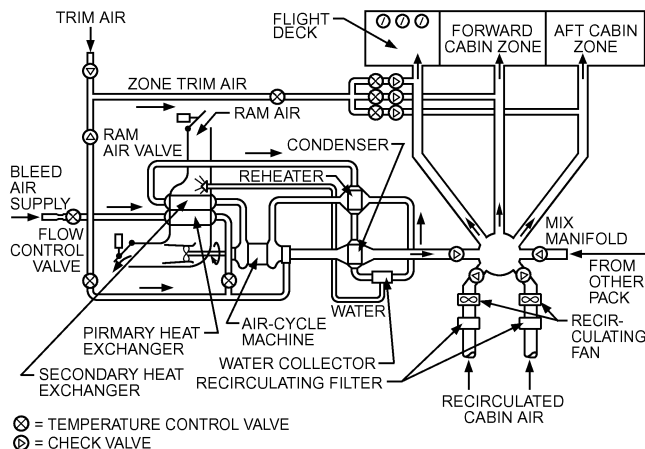
Fig. 8   Typical Aircraft Air-Conditioning Schematic

controller, selector panel, and redundant positive-pressure relief valves. Provisions for negative-pressure relief are incorporated in the relief valves and/or included in the aircraft structure (door). The system controls the cabin ascent and descent rates to acceptable comfort levels, and maintains cabin pressure altitude in accordance with cabin-to-ambient differential pressure schedules. Modern controls usually set landing field altitude if not available from the flight management system (FMS), and monitor aircraft flight via the FMS and the air data computer (ADC) to minimize the cabin pressure altitude and rate of change.

The cabin pressure modulating valves and safety valves (positive-pressure relief valves) are located either on the aircraft skin in the case of large commercial aircraft, or on the fuselage pressure bulkhead in the case of commuter, business, and military aircraft. Locating the outflow valves on the aircraft skin precludes the handling of large airflows in the unpressurized tailcone or nose areas and provides some thrust recovery; however, these double gate valves are more complex than the butterfly valves or poppet valves used for bulkhead installations. The safety valves are poppet valves for either installation. Most commercial aircraft have electronic controllers located in the E/E bay. The cabin pressure selector panel is located in the flight deck.

TYPICAL FLIGHT

A typical flight scenario from London's Heathrow Airport to Los Angeles International Airport would be as follows:

While the aircraft is at the gate, the ECS can be powered by bleed air supplied by the auxiliary power unit (APU), bleed air from a ground cart, or bleed air from the main engines after engine start. The APU or ground-cart bleed air is ducted directly to the bleed air manifold upstream of the air-conditioning packs. Engine bleed air is preconditioned by the engine bleed air system prior to being ducted to the air-conditioning packs. The air-conditioning packs are normally switched to operation using engine bleed air after the engines are started.

Taxiing from the gate at Heathrow, the outside air temperature is 59°F with an atmospheric pressure of 14.7 psia. The aircraft engines are at low thrust, pushing the aircraft slowly along the taxiway.

Engine Bleed Air Control

As outside air enters the compressor stages of the engine, it is compressed to 32 psia and a temperature of 330°F. Some of this air is then extracted from the engine core through one of two bleed port openings in the side of the engine. Which bleed port extracts the air depends on the positioning of valves that control the ports. One bleed port is at the engine's fifteenth compressor stage, commonly called high stage. The second is at the eighth compressor stage, commonly called low stage or intermediate stage. The exact stage varies depending on engine type. The high stage is the highest air pressure available from the engine compressor. At low engine power, the high stage is the only source of air at sufficient pressure to meet the needs of the bleed system. The bleed system is totally automatic, except for a shutoff selection available to the pilots on the overhead panel in the flight deck.

As the aircraft turns onto the runway, the pilots advance the engine thrust to takeoff power. The engine's high stage compresses the air to 1200°F and 430 psia. This energy level exceeds the requirements for the air-conditioning packs and other pneumatic services; approximately 50% of the total energy available at the high-stage port cannot be used. However, the bleed system automatically switches to the low-stage port, which conserves energy.

Because the engine must cope with widely varying conditions from ground level to flight at an altitude of up to 43,100 ft, during all seasons and throughout the world, the air at the high or low stage of the engine compressor will seldom exactly match the needs of the pneumatic systems. Excess energy must be discarded as waste heat.
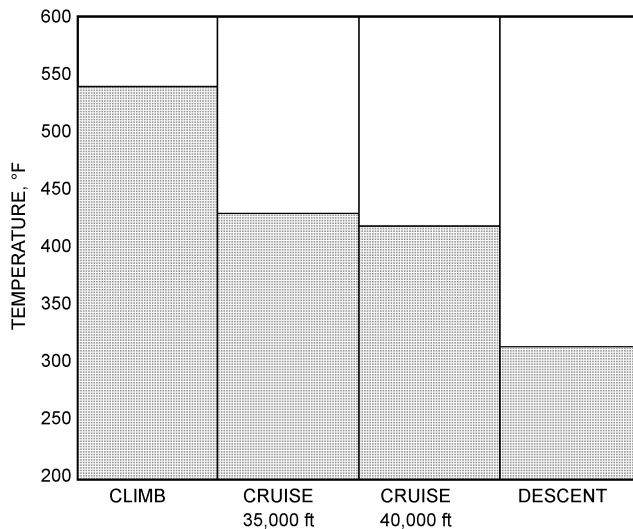
Fig. 9　Typical Air Temperature Supplied to Bleed System During Flight
(Hunt et al. 1995)

The bleed system constantly monitors engine conditions and selects the least wasteful port. Even so, bleed temperatures often exceed safe levels at which fuel will not auto-ignite. The precooler automatically discharges excess energy to the atmosphere to ensure that the temperature of the pneumatic manifold is well below that which could ignite fuel. The precooler is particularly important in the event of a fuel leak.

The aircraft climbs to a cruise altitude of 39,000 ft, where the outside air temperature is −70°F at an atmospheric pressure of 2.9 psia, and the partial pressure of oxygen is 0.5 psi. Until the start of descent to Los Angeles, the low compressor stage is able to compress the low-pressure cold outside air to more than 30 psia and a temperature above 400°F. This conditioning of the air is all accomplished through the heat of compression—fuel is added only after the air has passed through the compressor stages of the engine core.

Figure 9 shows the temperature of the air being extracted from the engine compressor to the bleed system from the time of departure at London to the time of arrival at Los Angeles. The temperature of the air supplied to the bleed system far exceeds that required to destroy any microorganisms present in the outside air during any point of the trip. At cruising altitudes, outside air contains very few biological particles (a few dark fungal spores per cubic metre of air), although there are higher concentrations at lower altitudes. Because of the high air temperatures from the engine compressor, the air supplied to the air-conditioning packs is sterile.

Air leaving the bleed system while in cruise enters the pneumatic manifold at 400°F and 30 psia. The air then passes through an ozone converter on its way to the air-conditioning packs located under the wing at the center of the aircraft.

Ozone Protection

While flying at 39,000 ft, several ozone plumes are encountered. Some have ozone concentrations as high as 0.8 parts per million (ppm) or 0.62 ppm sea level equivalent (SLE). This assumes a worst-case flight during the month of April, when ozone concentrations are highest. If this concentration of ozone were introduced into the cabin, passengers and crew could experience some chest pain, coughing, shortness of breath, fatigue, headache, nasal congestion, and eye irritation.

Atmospheric ozone dissociation occurs when the ozone goes through the compressor stages of the engine, the ozone catalytic converter (which is on aircraft with a route structure that can encounter

high ozone concentrations), and the air-conditioning packs. The ozone further dissociates when contacting airplane ducts, interior surfaces, and the airplane recirculation system. The ozone converter dissociates ozone to oxygen molecules by the catalyzing action of a noble catalyst such as palladium. A new converter dissociates approximately 95% of the ozone entering the converter to oxygen. It has a useful life of about 12,000 flight hours.

As the air leaves the ozone converter, it is still at 400°F and a pressure of 30 psia. Assuming a worst case when the converter is approaching the end of its useful life with an ozone conversion efficiency of 60%, the ozone concentration leaving the converter is about 0.25 ppm SLE. This air goes through the air-conditioning packs and enters the cabin. The ozone concentration in the cabin is about 0.09 ppm. As mentioned in the section on Regulations, the FAA sets a three-hour time-weighted average ozone concentration limit in the cabin of 0.1 ppm and a peak ozone concentration limit of 0.25 ppm.

Air-Conditioning and Temperature Control

The air next enters the air-conditioning packs, which provide essentially dry, sterile, and dust-free conditioned air to the airplane cabin at the proper temperature, flow rate, and pressure to satisfy pressurization and temperature control requirements. For most aircraft, this is approximately 5 cfm per passenger. To ensure redundancy, two air-conditioning packs (two are typical, some aircraft have more) provide a total of about 10 cfm of conditioned air per passenger. An equal quantity of filtered, recirculated air is mixed with the air from the air-conditioning packs for a total of approximately 20 cfm per passenger. This quantity of supply air results in a complete cabin air exchange about every 2.5 min, or about 25 air changes per hour. The high air exchange rate is necessary to control temperature gradients, prevent stagnant cold areas, maintain air quality, and dissipate smoke and odors in the cabin. Temperature control is the predominant driver of outside airflow requirements.

The automatic control for the air-conditioning packs constantly monitors airplane flight parameters, the flight crew's selection for the temperature zones, the cabin zone temperature, and the mixed distribution air temperature. The control automatically adjusts the various valves for a comfortable environment under normal conditions. The pilot's controls are located on the overhead panel in the flight deck along with the bleed system controls. Normally, pilots are required only to periodically monitor the compartment temperatures from the overhead panel. Temperatures can be adjusted based on flight attendant reports of passengers being too hot or too cold. Various selections are available to the pilots to accommodate abnormal operational situations.

Air Recirculation

The air has now been cooled and leaves the air-conditioning packs. It leaves the packs at 60°F and 11.8 psi. The relative humidity is less than 5% and ozone concentration is less than 0.25 ppm. The carbon dioxide concentration remains unchanged from that of the outside air at about 350 ppm. As this air enters a mixing chamber, it is combined with an equal quantity of filtered recirculated air.

The recirculated air entering the mix manifold is essentially sterile. Over 99.9% of the bacteria and viruses produced by the passengers are removed by HEPA filters, which are used on most modern aircraft. The filters cannot be bypassed and become more efficient with increased service life. They do, however, require replacement at periodic maintenance intervals. Gases, which are not removed by the filters, are diluted to low levels with outside air at a high exchange rate of about 12.5 times per hour.

Air Distribution

The air flows from the mix manifold into duct risers dedicated to each seating zone. The risers direct the air from below the floor to the overhead cabin ventilation system. Trim air (hot bleed air from the pneumatic manifold) is added in the risers to increase the air

temperature, if needed. The supply air temperature per seating zone can vary due to differences in seating densities between seating zones.

The overhead air distribution network runs the length of the cabin. The air is dust free and sterile with a relative humidity of 10 to 20%. The temperature is 65 to 85°F, depending on the seating zone the air is being supplied to, and the carbon dioxide concentration is about 1050 ppm. The carbon dioxide is generated by passenger respiration.

Because of the large quantity of air entering the relatively small volume of the cabin, as compared to a building, control of the airflow patterns is required to give comfort without draftiness. Air enters the passenger cabin from overhead distribution outlets that run the length of the cabin. These outlets create circular airflow patterns in the cabin (Figure 5). Air leaves the outlets at a velocity of more than 500 fpm, becomes entrained with cabin air, and maintains sufficient momentum to sweep the cabin walls and floor and to wash out any cold pockets of air in the cabin. The air direction is oriented to avoid exposed portions of a seated passenger, such as the arms, hand, face, neck, and legs, yet it is of sufficient velocity to avoid the sensation of stagnant air. This requires seated passenger impingement velocities between 20 and 70 fpm.

The air volume circulates in the cabin while continuously mixing with cabin air for 2 to 3 min before it enters the return air grilles that are located in the sidewalls near the floor and run the length of the cabin along both sides. While this air is in the cabin, about 0.33% of the oxygen is consumed by human metabolism. The oxygen is replaced by an equal quantity of carbon dioxide from passenger respiration. In addition, the return air entrains microorganisms or other contaminants from passengers or the cabin itself. Approximately one-half of the return air is exhausted overboard and the other half recirculated to sterile conditions through HEPA filters.

In the aft section, exhaust air is extracted by the cabin pressure outflow valve and exhausted overboard. In the forward section, it is continuously extracted from below the floor by recirculation fans, filtered, and then mixed with the outside air being supplied by the air-conditioning packs.

The cabin ventilation is balanced so that air supplied at one seat row leaves at approximately the same seat row. This minimizes airflow in the fore and aft directions, to minimize the spread of passenger-generated contaminants.

Cabin Pressure Control

The cabin pressure control continuously monitors ground and flight modes, including altitude, climb, cruise or descent modes, as well as the airplane's holding patterns at various altitudes. It uses this information to position the cabin pressure outflow valve to maintain cabin pressure as close to sea level as practical, without exceeding a cabin-to-outside pressure differential of 8.60 psi. At a 39,000 ft cruise altitude, the cabin pressure is equivalent to 6900 ft, or a pressure of 11.5 psia. In addition, the outflow valve repositions itself to allow more or less air to escape as the airplane changes altitude. The resulting cabin altitude is consistent with airplane altitude within the constraints of keeping pressure changes comfortable for passengers. Normal pressure change rates are 0.26 psi/min ascending and 0.16 psi/min descending.

The cabin pressure control system panel is located in the pilot's overhead panel near the other air-conditioning controls. Normally, the cabin pressure control system is totally automatic, requiring no attention from the pilots.

AIR QUALITY

Aircraft cabin air quality is a complex function of many variables including ambient air quality, the design of the cabin volume, the design of the ventilation and pressurization systems, the way the systems are operated and maintained, the presence of sources of contaminants, and the strength of such sources. The following factors can individually or collectively affect aircraft cabin air quality.

Airflow

The total volume of air is exchanged approximately every 2.5 to 3 min in a wide-body aircraft, and every 2 to 3 min on a standard-body aircraft. The airflow per unit length of the airplane is similar for all sections. However, economy class has a lower airflow per passenger because of its greater seating density as compared to first class and business class. A high air exchange rate and sufficient quantity of outside air is supplied to each cabin zone to maintain air quality, control temperature gradients, prevent stagnant cold areas, and dissipate smoke and odors in the cabin.

The flight deck is provided with a higher airflow per person than the cabin in order to maintain a positive pressure in the cockpit (1) to prevent smoke ingress from adjacent areas (abnormal condition), (2) to provide cooling for electrical equipment, (3) to account for increased solar loads and night heat loss through the airplane skin and windows, and (4) to minimize temperature gradients.

Typical commercial transport aircraft provide approximately 50% conditioned (outside) and 50% filtered recirculated air to the passenger cabin on a continuous basis. Increasing the quantity of outside air beyond 50% to the cabin would lower the cabin CO_2 concentration slightly, but it would also increase the potential cabin ozone concentration and lower the cabin relative humidity.

The recirculated air is cleaned by drawing it through HEPA filters that cannot be bypassed. The air distribution system is designed to provide approximately 10 cfm outside air and 10 cfm filtered, recirculated air per passenger. A fully loaded, all-tourist-class passenger aircraft, which has the maximum seating density throughout the airplane, provides an outside airflow per passenger of 6.5 (standard-body) to 8 cfm (wide-body).

The outside air quantity supplied on some aircraft models can be lowered by shutting off one air-conditioning pack. The flight crew has control of these packs to provide flexibility in case of a system failure or for special use of the aircraft. Packs should be in full operation whenever passengers are on board.

Environmental Tobacco Smoke (ETS)

Currently, there are no governmental, occupational, or ambient standards for environmental tobacco smoke (ETS). However, in 1986, the National Academy of Sciences recommended banning smoking on U.S. domestic flights to eliminate the possibility of fires caused by cigarettes, to lessen irritation and discomfort to passengers and crew, and to reduce potential health hazards.

On flights where smoking is allowed, ETS in the cabin is controlled indirectly by controlling the concentration of carbon monoxide (CO) and respirable suspended particulates (RSP). CO and RSP are tracer constituents of ETS and several standards do list acceptable maximum levels for these constituents. Table 3 in Chapter 9 of the 2005 *ASHRAE Handbook—Fundamentals* summarizes these standards. This method of control does not consider other constituents present in ETS.

Measured CO levels in aircraft smoking section(s) during peak smoking are within acceptable limits. RSP concentrations in smoking sections can exceed recommended levels during peak smoking, which is also true of most heavy-smoking areas (e.g. restaurants, bowling alleys, etc.). Of 92 airplanes tested in a DOT-sponsored study, average RSP values of 40 $\mu g/m^3$ and 175 $\mu g/m^3$ were measured in nonsmoking and smoking sections, respectively.

Ozone

Ozone is present in the atmosphere as a consequence of the photochemical conversion of oxygen by solar ultraviolet radiation. Ozone levels vary with season, altitude, latitude, and weather systems. A marked and progressive increase in ozone concentration occurs with an increase in the flight altitude of commercial aircraft.

The mean ambient ozone concentration increases with increasing latitude, is maximal during the spring (fall season for southern hemisphere), and often varies when weather causes high ozone plumes to descend.

Residual cabin ozone concentration is a function of the ambient concentration, the design of the air distribution system and how it is operated and maintained, and whether catalytic ozone converters are installed.

Cabin ozone limits are set by FAR 121.578 and FAR 25.832. The use of catalytic ozone converters is generally required on airplanes flying mission profiles where the cabin ozone levels are predicted to exceed these FAR limits (refer to the FAA Code of Federal Regulations for other compliance methods).

Microbial Aerosols

Biologically derived particles that become airborne include viruses, bacteria, actinomycetes, fungal spores and hyphae, arthropod fragments and droppings, and animal and human dander. Only one study has documented the occurrence of an outbreak of infectious disease related to airplane use. In 1977, because of an engine malfunction, an airliner with 54 persons onboard was delayed on the ground for 3 h, during which the airplane ventilation system was reportedly turned off. Within 3 days of the incident, 72% of the passengers became ill with influenza. One passenger (the index case) was ill while the airplane was delayed (Moser et al. 1979).

With the ventilation system shut off, no fresh air was introduced into the cabin to displace microbial aerosols and CO_2 or to control cabin temperatures. It is believed that, had the ventilation system been operating during the delay, the possibility of other passengers becoming ill would have been minimal.

The airplane ventilation system should never be shut off when passengers are on board; an exception to this recommendation is during no-pack takeoffs when the air packs (but not the recirculation fans) are shut off for the short time only on takeoff.

To remove particulates and biological particles from the recirculated air, filter assemblies that contain a HEPA filter with a minimum efficiency of 94 to 99.97% DOP as measured by MIL-STD-282 should be used. A HEPA filter is rated using 0.3 μm size particles. A filter's efficiency increases over time as particulates become trapped by the filter. Due to the overlap of capture mechanisms in a filter, the efficiency also increases for particles smaller and larger than the most penetrating particle size (MPPS). For an airplane filter, the MPPS is about 0.1 to 0.2 μm.

The efficiency of a filter that can remove 0.003 μm particles from the air is in excess of 99.9+%. Most bacteria (99%) are larger than 1 μm. Viruses are approximately 0.003 to 0.05 μm in size. Test results in a DOT study conducted on 92 randomly selected flights showed that bacteria and fungi levels measured in the airplane cabin are similar to or lower than those found in the home. These low microbial contaminant levels are due to the large quantity of outside airflow and high filtration of the recirculation system.

Volatile Organic Compounds

Volatile organic compounds (VOCs) can be emitted by material used in furnishings, pesticides, disinfectants, cleaning fluids, and food and beverages. In-flight air quality testing on revenue flights sponsored by The Boeing Company and the Air Transport Association of America (ATAA 1994) detected trace VOC quantities that were considered well below levels that could result in adverse health effects.

Carbon Dioxide

Carbon dioxide is the product of normal human metabolism, which is the predominant source in aircraft cabins. The CO_2 concentration in the cabin varies with outside air rate, the number of people present, and their individual rates of CO_2 production, which vary with activity and (to a smaller degree) with diet and health.

Carbon dioxide has been widely used as an indicator of indoor air quality, typically serving the function of a surrogate. Per a DOT-sponsored study, measured cabin CO_2 values of 92 randomly selected smoking and nonsmoking flights average 1500 ppm.

The Environmental Exposure Limit adopted by the American Conference of Governmental Industrial Hygienists (ACGIH) is 5000 ppm as the time-weighted average (TWA) limit for CO_2; this value corresponds to a fresh air ventilation rate of 2.3 cfm per person. The TWA is the concentration, for a normal 8 h workday and a 40 h workweek, to which nearly all workers can be repeatedly exposed, day after day, without adverse effects. As mentioned in the Regulations section under Ventilation, a FAR also limits CO_2 to 5000 ppm (0.5%). Aircraft cabin CO_2 concentrations are below this limit.

ASHRAE *Standard* 62, which does not apply to aircraft per se, states, "Comfort (odor) criteria are likely to be satisfied if the ventilation rate is set so that 1000 ppm CO_2 is not exceeded." It further states, "This level is not considered a health risk but is a surrogate for human comfort (odor)." An interpretation of this standard noted that 1000 ppm CO_2 is not a requirement of the standard, but it can be considered a target concentration level. *[Editor's note: see ASHRAE (2004) for an update to this standard.]*

Humidity

The relative humidity in airplanes tested in a DOT-sponsored study ranged from approximately 5 to 35% with an average of 15 to 20%. The humidity is made up mainly of moisture from passengers and will increase with more passengers and decrease with increased outside airflow. A major benefit of filtered, recirculated air supplied to the passenger cabin is an increase in cabin humidity compared to airplanes with only outside supply air.

After three or four hours of exposure to relative humidity in the 5 to 10% range, some passengers may experience dryness of the eyes, nose, and throat. However, no serious adverse health effects of low relative humidity on the flying population have been documented.

Cabin Pressure/Oxygen

At a normal airplane cruise altitude, aircraft cabins are pressurized to a maximum cabin altitude of 8000 ft (to compress ambient air to a physiologically acceptable form). A DOT-sponsored National Academy of Sciences study concluded that current pressurization criteria and regulations are generally adequate to protect the traveling public. The Academy also noted that the normal maximum rates of change of cabin pressure (approximately 500 ft/min in increasing altitude and 300 ft/min in decreasing altitude) are such that they do not pose a problem for the typical passenger.

However, pressurization of the cabin to equivalent altitudes of up to 8000 ft, as well as changes in the normal rates of pressure during climb and descent, may create discomfort for people suffering from upper respiratory or sinus infections, obstructive pulmonary diseases, anemias, or certain cardiovascular conditions. In those cases, supplemental oxygen may be recommended. Children and infants sometimes experience discomfort or pain because of pressure changes during climb and descent. Injury to the middle ear has occurred to susceptible people, but is rare.

Some articles and reports state that substandard conditions exist in airplane cabins due to a lack of oxygen, attributed in some reports to reduced fresh air ventilation rates or the use of recirculated air. These arguments imply that the oxygen content of cabin air is depleted through consumption by occupants. Humans at rest breathe at a rate of approximately 0.32 cfm, while consuming oxygen at a rate of 0.015 cfm. The percent oxygen makeup of the supply air remains at approximately 21% at cruise altitude. A person receiving 10 cfm of outside air and 10 cfm of recirculation air would therefore receive approximately 4.2 cfm of oxygen. Consequently,

the content of oxygen in cabin air is little affected by breathing as it is replaced in sufficient quantities compared to the human consumption rate.

Although the percentage of oxygen in cabin air remains virtually unchanged (21%) at all flight altitudes, the partial pressure of oxygen decreases with increasing altitude, which decreases the amount of oxygen available to the blood's hemoglobin. The increase in cabin altitude may cause low-grade hypoxia (reduced tissue oxygen levels) in some people. The National Academy of Sciences concluded that pressurization of the cabin to an equivalent altitude of 5000 to 8000 ft is physiologically safe for healthy individuals—no supplemental oxygen is needed to maintain sufficient arterial oxygen saturation. However, people with chronic pulmonary disease, cardiovascular disease, and anemia could be at risk at these cabin altitudes.

Multiple Factors

Multiple factors can influence comfort, and cabin air quality is a function of several parameters. These cabin environmental parameters, in combination with maintenance, operations, and individual and job-related factors, collectively influence the cabin crew and passenger perceptions of the cabin environment. The collective influence of these factors is acknowledged by the Aerospace Medical Association (AsMA) in a Special Committee report on Cabin Air Quality (Thibeault 1997), which cites factors such as hypoxia, decreased barometric pressure, crowding, inactivity, temperature control, jet lag, noise, three-dimensional motion, fear, stress, individual health, alcohol consumption, etc.

Figure 10 shows the three groups that can influence cabin environmental comfort: manufacturers, airlines, and the occupants themselves. Airplane manufacturers influence the physical environment by the design of the environmental control system integrated with the rest of the systems on the airplane. Airlines affect the environmental conditions in the cabin by seating configuration, amenities offered, and procedures for maintaining and operating the aircraft. Finally, cabin environmental comfort is influenced by the individual and job-related activities of the cabin crew and passengers.

Fig. 10   Airplane Cabin Environment Wheel
(Adapted, with permission, from STP 1393—Air Quality and Comfort in Airliner Cabins, copyright ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19428)

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CHAPTER 11

SHIPS

THIS chapter covers air conditioning for oceangoing surface vessels, including luxury liners, tramp steamers, oil rigs, and naval vessels. Although the general principles of air conditioning for land installations also apply to marine applications, factors such as weight, size, and corrosion resistance take on greater importance, and new factors (e.g., tolerance for pitch and roll and shipboard vibration) come into play.

The importance of shipboard air conditioning depends on a ship's mission. On passenger vessels that focus completely on passenger comfort, such as cruise ships and casino vessels, air conditioning is vital. Aboard commercial vessels (tankers, bulkers, container ships, etc.) air conditioning provides an environment in which personnel can live and work without heat stress. Shipboard air conditioning also improves reliability of electronic and other critical equipment, as well as weapons systems aboard naval ships.

This chapter discusses merchant ships, which includes passenger and commercial vessels, and naval surface ships. In general, the details of merchant ship air conditioning also apply to warships. However, all ships are governed by their specific ship specifications, and warships are often also governed by military specifications, which ensure air-conditioning system and equipment performance in the extreme environment of warship duty.

MERCHANT SHIPS

Load Calculations

The cooling load estimate considers the following factors discussed in Chapter 30 of the 2005 *ASHRAE Handbook—Fundamentals*:

• Solar radiation
• Heat transmission through hull, decks, and bulkheads
• Heat (latent and sensible) dissipation from occupants
• Heat gain from lights
• Heat (latent and sensible) gain from ventilation air
• Heat gain from motors or other electrical equipment
• Heat gain from piping, machinery, and equipment

The heating load estimate should include the following:

• Heat losses through decks and bulkheads
• Ventilation air
• Infiltration (when specified)

In addition, the construction and transient nature of ships present some complications, as addressed in the following:

SNAME. The Society of Naval Architects and Marine Engineers (SNAME) *Technical and Research Bulletin* 4-16 can be used as a guide for shipboard load calculations.

The preparation of this chapter is assigned to TC 9.3, Transportation Air Conditioning.

ISO. 7547:2002 The International Organization for Standardization's (ISO) *Standard* 7547 discusses design conditions and calculations for marine HVAC systems.

Outside Ambient Temperature and Humidity. The service and type of vessel determine the proper outside design temperature, which should be based on temperatures prevalent in a ship's area of operation. Chapter 28 of the 2005 *ASHRAE Handbook—Fundamentals*, should be used to select ambient conditions, with special attention paid to high wet-bulb data; a ship's load is often driven by the latent load associated with the outside air. It is also common for different locations to be used for cooling and heating criteria. In general, for cooling, outside design conditions are 95°F db and 78°F wb; for semitropical runs, 95°F db and 80°F wb; and for tropical runs, 95°F db and 82°F wb. For heating, 0°F is usually the design temperature, unless the vessel will always operate in warmer climates. Design temperatures for seawater are 90°F in summer and 28°F in winter.

Solar Gain. Ships require special consideration for solar gain because (1) they do not constantly face in one direction and (2) the reflective properties of water increase solar load on outside boundaries not directly exposed to sunlight. For compartments with only one outside boundary, the temperature difference (outside dry-bulb temperature – inside dry-bulb temperature) across horizontal surfaces should be increased by 50°F and vertical surfaces by 30°F. For compartments with more than one outside boundary, the temperature difference should be increased by 35°F for horizontal surfaces and 20°F for vertical surfaces. For glass surfaces, the solar cooling load (SCL) is taken to be 160 Btu/h·ft^2 for spaces with one outside boundary and 120 Btu/h·ft^2 for spaces with more than one outside boundary.

Infiltration. Infiltration through weather doors is generally disregarded. However, specifications for merchant ships occasionally require an assumed infiltration load for heating steering gear rooms and the pilothouse.

Transmission Between Spaces. For heating loads, heat transmission through boundaries of machinery spaces in either direction is not considered. Allowances are not made for heat gain from warmer adjacent spaces. For cooling loads, the cooling effect of adjacent spaces is not considered unless temperatures are maintained with refrigeration or air-conditioning equipment.

Ventilation Requirements. Ventilation must meet the requirements of ASHRAE *Standard* 62.1, unless otherwise stated in the ship's specification.

Heat Transmission Coefficients. The overall heat transmission coefficients *U* for the composite structures common to shipboard construction do not lend themselves to theoretical derivation; they are usually obtained from full-scale panel tests. SNAME *Bulletin* 4-7 gives a method to determine these coefficients when tested data are unavailable. ISO *Standard* 7547 also gives some guidance in this area.

Inside Air Temperature and Humidity. Thermal environmental conditions for human occupancy are given in ASHRAE *Standard* 55.

11.1

People. Ships normally carry a fixed number of people. The engineer must select the location where the ship's fixed complement of people creates the greatest heat load, and then not apply the people load elsewhere. Note that occupants are only counted once when determining the chiller or condensing-unit load; however, air coils in each zone must be capable of removing the heat load associated with the maximum number of people in the zone.

Ventilation in the zone can also be reduced when occupants are not present. For the ventilation load, occupants are counted once, in the location where they create the greatest ventilation requirement. The practical way to apply this concept is by measuring CO_2 levels in a space and adjusting outside air accordingly. Although using this principle can reduce required chiller or condensing-unit capacity on all ships, it is most significant aboard passenger ships.

Equipment

In general, equipment used for ships is much more rugged than that for land use. Sections 6 through 10 of ASHRAE *Standard* 26 list HVAC equipment requirements for marine applications. When selecting marine duty air-conditioning equipment, the following should be considered:

- It should function properly under dynamic roll and pitch and static trim and heel conditions. This is especially important for compressor oil sumps, oil separators, refrigerant drainage from a condenser and receiver, accumulators, and condensate drainage from drain pans.
- Construction materials should withstand the corrosive effects of salt air and seawater. Materials such as stainless steel, nickel-copper, copper-nickel, bronze alloys, and hot-dipped galvanized steel are used extensively.
- It should be designed for uninterrupted operation during the voyage and continuous year-round operation. Because ships en route cannot be easily serviced, some standby capacity, spare parts for all essential items, and extra refrigerant charge should be carried.
- It should have no objectionable noise or vibration, and must meet noise criteria required by the ship's specification.
- It should occupy minimum space, commensurate with its cost and reliability. Weight should also be minimized.
- A ship may pass through one or more complete cycles of seasons on a single voyage and may experience a change from winter to summer operation in a matter of hours. Systems should be flexible enough to compensate for climatic changes with minimal attention from the ship's crew.

The following general items should be considered when selecting specific air conditioning components:

Fans. Fans must be selected for stable performance over their full range of operation and should have adequate isolation to prevent transmitting vibration to the deck. Because fan rooms are often adjacent to or near living quarters, effective sound treatment is essential.

Cooling Coils. If more than 30% outside air is brought across a cooling coil, the use of copper tube, copper fin, or epoxy-coated coils must be considered. To account for the ship's movement, drain pans should have two drain connections. Because of size constraints, care must be taken to prevent moisture carryover. Face velocity limits (in fpm) for different coil materials and different fin spacing are as follows:

Face Velocity Limits, fpm

Fins per Inch (fpi	Aluminum Fins	Copper or Coated Fins
8	550	500
11	550	425
14	550	375

Off-coil temperatures are another concern. Ships typically have low ceiling heights and can not tolerate low air-introduction temperatures. Typically 55°F db and 54°F wb are used as limiting off-coil temperatures.

Electric Heaters. U.S. Coast Guard (USCG) approved sheathed heaters are typically required. The only exception is when the electric heaters, approved by a regulatory body such as UL, are incorporated in a packaged unit.

Air Diffusers. Care must be taken with the selection of air diffusers because of the low ceilings typical of shipboard applications.

Air-Conditioning Compressors. Compressors of all types are used for marine applications. Care must be taken when using a non-positive-displacement compressor (such as centrifugal) because low-load, high-condensing temperature is a common off-load condition.

When high discharge temperatures are a concern, seawater-cooled heads are not normally an option; other methods such as fan cooling or liquid injection must be considered for maintaining acceptable discharge temperatures.

Whenever possible, compressors should be the same types used for ship's service and cargo refrigeration, except for the number of cylinders or the speed (see Chapter 31 in the 2006 *ASHRAE Handbook—Refrigeration*).

Typical Systems

All types of systems may be considered for each marine application. The systems are the same as in land applications; the difference is the relative weighting of their advantages and disadvantages for marine use. This section does not review all the systems used aboard ships, but rather some of the more common ones.

Direct refrigerant cooling systems are often used for small, single-zone applications. Aboard ships, places like control rooms and pilot houses lend themselves to a direct refrigerant system. For larger spaces, air distribution is of more concern; direct refrigerant cooling is thus less likely to be the optimum solution.

Two-pipe and **four-pipe fan coil systems** are often used for large systems. The water piping used in these systems takes up only a fraction of the space used by an all-air ducted system. The disadvantage is fan noise in the space being cooled.

Many types of **all-air systems** are used aboard ships. Space, cost, noise, and complexity are among the leading parameters when comparing different all-air systems. Using high-velocity air distribution for an all-air system offers many advantages; unitary (factory-assembled) central air-handling equipment and prefabricated piping, clamps, and fittings facilitates installation for both new construction and conversions. Substantial space-saving is possible compared to conventional low-velocity sheet metal ducts. Maintenance is also reduced. Noise is the one major drawback of a high-velocity system, which many times leads to selection of a low-velocity system.

Terminal reheat air conditioning (described in Chapter 2 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*) is commonly used because of its simplicity and good zone control characteristics. However, as systems become larger the energy inefficiency of this system becomes a significant drawback.

Dual-duct systems (also described in Chapter 2 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*) have the following advantages:

- All conditioning equipment is centrally located, simplifying maintenance and operation
- Can heat and cool adjacent spaces simultaneously without cycle changeover and with minimum automatic controls
- Because only air is distributed from fan rooms, no water or steam piping, electrical equipment, or wiring are in conditioned spaces

The major drawback is the inability to finely control temperature and humidity. This disadvantage is enough to preclude using these systems in many passenger vessel applications.

Aboard ships, **constant-volume systems** are most common. Their advantages include simplicity (for maintenance, operation, and repair) and low cost. However, for large passenger vessels, the energy efficiency and the tight control of zone temperature make **variable-volume/temperature systems** very attractive.

Air Distribution Methods

Good air distribution in staterooms and public spaces is difficult to achieve because of low ceiling heights and compact space arrangements. Design should consider room dimensions, ceiling height, volume of air handled, air temperature difference between supply and room air, location of berths, and allowable noise. For major installations, mock-up tests are often used to establish exacting performance criteria.

Air usually returns from individual small spaces either by a sight-tight louver mounted in the door or by an undercut in the door leading to the passageway. An undercut door can only be used with air quantities of 75 cfm or less. Louvers are usually sized for face velocity of 400 fpm based on free area.

Ductwork on merchant ships is constructed of steel. Ducts, other than those requiring heavier construction because of susceptibility to damage or corrosion, are usually made with riveted seams sealed with hot solder or fire-resistant duct sealer, welded seams, or hooked seams and laps. They are made of hot-dipped, galvanized, copper-bearing sheet steel, suitably stiffened externally. The minimum thickness of material is determined by the diameter of round ducts or by the largest dimension of rectangular ducts, as listed in Table 1.

The increased use of high-velocity, high-pressure systems has resulted in greater use of prefabricated round pipe and fittings, including spiral-formed sheet metal ducts. It is important that field-fabricated ducts and fittings be airtight. Using factory-fabricated fittings, clamps, and joints effectively minimizes air leakage for these high-pressure ducts.

In addition to the space advantage, small ductwork saves weight, another important consideration for this application.

Control

The conditioning load, even on a single voyage, varies over a wide range in a short period. Not only must the refrigeration plant meet these load variations, but the controls must readily adjust the system to sudden climatic changes. Accordingly, it is general practice to equip the plant with automatic controls.

Regulatory Agencies

Merchant vessels that operate under the U.S. flag come under the jurisdiction of the U.S. Coast Guard. Accordingly, the installation and components must conform to the Marine Engineering Rules and Marine Standards of the Coast Guard.

Comfort air-conditioning installations do not primarily come under the American Bureau of Shipping. However, certified pressure vessels and electric components approved by independent agencies (e.g., ASME, UL) must be used. Wherever possible, equipment should be manufactured to comply with the American Bureau of Shipping Rules and Regulations. This is important when vessels are equipped for carrying cargo refrigeration, because air-conditioning compressors may serve as standby units in the event of a cargo compressor failure. This compliance eliminates the need for a separate, spare cargo compressor. Safety of Life at Sea (SOLAS) is an agency that governs the use of fire dampers and duct wall thickness when passageways or fire boundaries are crossed.

NAVAL SURFACE SHIPS

Design Criteria

Outside Ambient Temperature. Design conditions for naval vessels have been established as a compromise, considering the large cooling plants required for internal heat loads generated by machinery, weapons, electronics, and personnel. Temperatures of 90°F db and 81°F wb are used for worldwide applications, with 85°F seawater temperatures. Heating-season temperatures are 10°F for outside air and 28°F for seawater.

Inside Temperature. Naval ships are generally designed for space temperatures of 80°F db with a maximum of 55% rh for most areas requiring air conditioning. The *Air Conditioning, Ventilation and Heating Design Criteria Manual for Surface Ships of the United States Navy* (USN 1969) gives design conditions established for specific areas. *Standard Specification for Cargo Ship Construction* (USMA 1965) gives temperatures for ventilated spaces.

Ventilation Requirements. Ventilation must meet the requirements of ASHRAE *Standard* 62, except when ship's specification requires otherwise.

Air-Conditioned Spaces. Naval ship design requires that air-conditioning systems serving living and berthing areas on surface ships replenish air in accordance with damage control classifications, as specified in USN (1969):

- Class Z systems: 5 cfm per person
- Class W systems for troop berthing areas: 5 cfm per person
- All other Class W systems: 10 cfm per person. The flow rate is increased only to meet either a 75 cfm minimum branch requirement or to balance exhaust requirements. Outside air should be kept at a minimum to minimize the size of the air-conditioning plant.

Load Determination

The cooling load estimate consists of coefficients from *Design Data Sheet* DDS511-2 of USN *General Specifications for Building Naval Ships* or USN (1969) and has allowances for the following:

- Solar radiation
- Heat transmission through hull, decks, and bulkheads
- Heat (latent and sensible) dissipation of occupants
- Heat gain from lights
- Heat (latent and sensible) gain from ventilation air
- Heat gain from motors or other electrical equipment
- Heat gain from piping, machinery, and equipment

Loads should be derived from requirements indicated in USN (1969). The heating load estimate should include the following:

- Heat losses through hull, decks, and bulkheads
- Ventilation air
- Infiltration (when specified)

Some electronic spaces listed in USN (1969) require adding 15% to the calculated cooling load for future growth and using one-third of the cooling-season equipment heat dissipation (less the 15% added for growth) as heat gain in the heating season.

Heat Transmission Coefficients. The overall heat transmission coefficient U between the conditioned space and the adjacent boundary should be estimated from *Design Data Sheet* DDS511-2. Where new materials or constructions are used, new coefficients may be used from SNAME (1980) or calculated using methods found in DDS511-2 and SNAME.

Heat Dissipation from People. USN (1969) gives heat dissipation values for people in various activities and room conditions.

Table 1 Minimum Thickness of Steel Ducts

All vertical exposed ducts	16 USSG	0.0598 in.
Horizontal or concealed vertical ducts		
less than 6 in.	24 USSG	0.0239 in.
6.5 to 12 in.	22 USSG	0.0299 in.
12.5 to 18 in.	20 USSG	0.0359 in.
18.5 to 30 in.	18 USSG	0.0476 in.
over 30 in.	16 USSG	0.0598 in.

Heat Gain from Sources Within the Space. USN (1969) gives heat gain from lights and motors driving ventilation equipment. Heat gain and use factors for other motors and electrical and electronic equipment may be obtained from the manufacturer or from Chapter 30 of the 2005 *ASHRAE Handbook—Fundamentals*.

Equipment Selection

The equipment described for merchant ships also applies to U.S. naval vessels, except as follows:

Fans. A family of standard fans is used by the navy, including vaneaxial, tubeaxial, and centrifugal fans. Selection curves used for system design are found on NAVSEA *Standard Drawings* 810-921984, 810-925368, and 803-5001058. Manufacturers are required to furnish fans dimensionally identical to the standard plan and within 5% of the delivery. No belt-driven fans are included.

Cooling Coils. The U.S. Navy uses eight standard sizes of direct-expansion and chilled-water cooling coils. All coils have eight rows in the direction of airflow, with a range in face area of 0.6 to 10.0 ft^2.

Coils are selected for a face velocity of 500 fpm maximum; however, sizes 54 DW to 58 DW may have face velocity up to 620 fpm if the bottom of the duct on the discharge is sloped up at 15° for a distance equal to the height of the coil. Construction and materials are specified in MIL-C-2939.

Chilled-water coils are most common and are selected based on 45°F inlet water with approximately a 6.7°F rise in water temperature through the coil. This is equivalent to 3.6 gpm per ton of cooling.

Heating Coils. The standard naval steam and electric duct heaters have specifications as follows:

Steam Duct Heaters
• Maximum face velocity is 1800 fpm
• Preheater leaving air temperature is 42 to 50°F
• Steam heaters are served from a 50 psig steam system

Electric Duct Heaters
• Maximum face velocity is 1400 fpm
• Temperature rise through the heater is per MIL-H-22594A, but is in no case more than 48°F.
• Power supply for the smallest heaters is 120 V, three-phase, 60 Hz. All remaining power supplies are 440 V, three-phase, 60 Hz.
• Pressure drop through the heater must not exceed 0.35 in. of water at 1000 fpm. Use manufacturers' tested data in system design.

Filters. Characteristics of the seven standard filter sizes the U.S. Navy uses are as follows:

• Filters are available in steel or aluminum
• Filter face velocity is between 375 and 900 fpm
• A filter-cleaning station on board ship includes facilities to wash, oil, and drain filters

Air Diffusers. Although it also uses standard diffusers for air conditioning, the U.S. Navy generally uses a commercial type similar to those used for merchant ships.

Air-Conditioning Compressors. In the past, the U.S. Navy primarily used reciprocating compressors up to approximately 150 tons; for larger capacities, open, direct-drive centrifugal compressors are used. On new designs, the U.S. Navy primarily uses rotary compressors (e.g., screw and centrifugal). R-134a is the U.S. Navy's primary refrigerant. Seawater is used for condenser cooling at 5 gpm per ton for reciprocal compressors and 4 gpm per ton for centrifugal compressors.

Typical Air Systems

On naval ships, zone reheat is used for most applications. Some ships with sufficient electric power use low-velocity terminal reheat systems with electric heaters in the space. Some newer ships use a fan-coil unit with fan, chilled-water cooling coil, and electric heating coil in spaces with low to medium sensible heat per unit area of

Table 2   Minimum Thickness of Materials for Ducts

	Sheet for Fabricated Ductwork			
	Nonwatertight		**Watertight**	
Diameter or Longer Side	**Galvanized Steel**	**Aluminum**	**Galvanized Steel**	**Aluminum**
Up to 6	0.018	0.025	0.075	0.106
6.5 to 12	0.030	0.040	0.100	0.140
12.5 to 18	0.036	0.050	0.118	0.160
18.5 to 30	0.048	0.060	0.118	0.160
Above 30	0.060	0.088	0.118	0.160

Welded or Seamless Tubing		
Tubing Size	**Nonwatertight Aluminum**	**Watertight Aluminum**
2 to 6	0.035	0.106
6.5 to 12	0.050	0.140

Spirally Wound Duct (Nonwatertight)		
Diameter	**Steel**	**Aluminum**
Up to 200	0.46	0.64
Over 200	0.76	0.81

Note: All dimensions in inches.

space requirements. The unit is supplemented by conventional systems serving spaces with high sensible or latent loads.

Air Distribution Methods

Methods used on naval ships are similar to those discussed in the section on Merchant Ships. The minimum thickness of materials for ducts is listed in Table 2.

Control

The navy's principal air-conditioning control uses a two-position dual thermostat that controls a cooling coil and an electric or steam reheater. This thermostat can be set for summer operation and does not require resetting for winter operation.

Steam preheaters use a regulating valve with (1) a weather bulb controlling approximately 25% of the valve's capacity to prevent freeze-up, and (2) a line bulb in the duct downstream of the heater to control the temperature between 42 and 50°F.

Other controls are used to suit special needs. Pneumatic/electric controls can be used when close tolerances in temperature and humidity control are required, as in operating rooms. Thyristor controls are sometimes used on electric reheaters in ventilation systems.

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CHAPTER 12

INDUSTRIAL AIR CONDITIONING

INDUSTRIAL facilities such as manufacturing plants, laboratories, processing plants, and nuclear power plants are designed for processes and environmental conditions that include proper temperature, humidity, air motion, air quality, and cleanliness. Generated airborne contaminants must be collected and treated before being discharged from the building or recirculated.

Many industrial buildings require large quantities of energy, both in manufacturing and maintaining building environmental conditions. Energy can be saved by proper use of insulation and ventilation, and by recovery of waste heat.

For worker efficiency, the building environment should be comfortable and healthful, and should minimize fatigue and facilitate communications. The HVAC systems should control temperature and humidity, have low noise levels, control health-threatening fumes, and provide spot cooling to prevent heat stress.

GENERAL REQUIREMENTS

Typical temperatures, relative humidities, and specific filtration requirements for storage, manufacture, and processing of various commodities are listed in Table 1. Requirements for a specific application may differ from those in the table. Improvements in processes and increased knowledge may cause further variations; thus, systems should be flexible to accommodate future requirements.

Inside temperature, humidity, cleanliness, and allowable variations should be established by agreement with the owner. A compromise between the requirements for product or process conditions and those for comfort may optimize quality and production costs.

An environment that allows a worker to perform assigned duties without fatigue from the effects of temperature and humidity results in better continuous performance. It may also improve morale and reduce absenteeism.

PROCESS AND PRODUCT REQUIREMENTS

A product or process may require control of one or more of the following factors.

Rate of Chemical Reaction

Some processes require temperature and humidity control to regulate chemical reactions. In rayon manufacturing, for example, pulp sheets are conditioned, cut to size, and mercerized. The temperature directly controls the rate of reaction, and the relative humidity maintains the solution at a constant strength and rate of evaporation.

In drying varnish, oxidizing depends on temperature. Desirable temperatures vary with the type of varnish. High relative humidity retards surface oxidation and allows internal gases to escape as chemical oxidizers cure the varnish from within. Thus, a bubble-free surface is maintained with a homogeneous film throughout.

Rate of Crystallization

The cooling rate determines the size of crystals formed from a saturated solution. Both temperature and relative humidity affect the cooling rate and change the solution density by evaporation.

In coating pans for pills, a heavy sugar solution is added to the tumbling mass. As water evaporates, sugar crystals cover each pill. Moving the correct quantity of air over the pills at the correct temperature and relative humidity forms a smooth opaque coating. If cooling and drying are too slow, the coating will be rough, translucent, and have an unsatisfactory appearance. If the cooling and drying are too fast, the coating will chip through to the interior.

Rate of Biochemical Reaction

Fermentation requires both temperature and humidity control to regulate the rate of biochemical reactions. Many fermentation vessels are jacketed to maintain consistent internal temperatures. Fermentors are held at different temperatures depending on the process involved. In brewing, typical fermentor temperatures range from 45 to 52°F. Because of vessel jacketing, tight control of room temperature may not be required. Usually, space temperatures should be held as close as practical to the process temperature inside the fermentation vessel.

Designing such spaces should take into account gases and other by-products generated by fermentation. Typically, carbon dioxide is the most prevalent by-product of fermentation in brewing and presents the greatest potential hazard if a fermentor overpressurizes the seal. Adequate ventilation should be provided in case carbon dioxide escapes the process.

In biopharmaceutical processes, hazardous organisms can escape a fermentor; design of spaces using those fermentors should allow containment. Heat gains from steam-sparged vessels should also be accounted for in such spaces.

Product Accuracy and Uniformity

Air temperature and cleanliness affect quality in manufacturing precision instruments, lenses, and tools. When manufacturing tolerances are within 0.0002 in., close temperature control prevents expansion and contraction of the material; constant temperature is more important than the temperature level. Usually, conditions are selected for personnel comfort and to prevent a film of moisture on the surface. A high-efficiency particulate air (HEPA) or ultralow-penetration air (ULPA) filter may be required.

Product Formability

Manufacturing pharmaceutical tablets requires close control of humidity for optimum tablet formation.

Moisture Regain

Air temperature and relative humidity markedly influence production rate and product mass, strength, appearance, and quality in manufacturing or processing hygroscopic materials such as textiles,

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The preparation of this chapter is assigned to TC 9.2, Industrial Air Conditioning.

Table 1   Temperatures and Humidities for Industrial Air Conditioning

Process	Dry Bulb, °F	rh, %	Process	Dry Bulb, °F	rh, %
ABRASIVE			**FOUNDRIES***		
Manufacture	79	50	Core making	60 to 70	
CERAMICS			Mold making		
Refractory	110 to 150	50 to 90	Bench work	60 to 70	
Molding room	80	60 to 70	Floor work	55 to 65	
Clay storage	60 to 80	35 to 65	Pouring	40	
Decalcomania production	75 to 80	48	Shakeout	40 to 50	
Decorating room	75 to 80	48	Cleaning room	55 to 65	

Use high-efficiency filtration in decorating room. To minimize the danger of silicosis in other areas, a dust-collecting system or medium-efficiency particulate air filtration may be required.

*Winter dressing room temperatures. Spot coolers are sometimes used in larger installations.

In mold making, provide exhaust hoods at transfer points with wet-collector dust removal system. Use 600 to 800 cfm per hood.

In shakeout room, provide exhaust hoods with wet-collector dust removal system. Exhaust 400 to 500 cfm in grate area. Room ventilators are generally not effective.

In cleaning room, provide exhaust hoods for grinders and cleaning equipment with dry cyclones or bag-type collectors. In core making, oven and adjacent cooling areas require fume exhaust hoods. Pouring rooms require two-speed powered roof ventilators. Design for minimum of 2 cfm per square foot of floor area at low speed. Shielding is required to control radiation from hot surfaces. Proper introduction of air minimizes preheat requirements.

Process	Dry Bulb, °F	rh, %
DISTILLING		
General manufacturing	60 to 75	45 to 60
Aging	65 to 72	50 to 60

Low humidity and dust control are important where grains are ground. Use high-efficiency filtration for all areas to prevent mold spore and bacteria growth. Use ultrahigh-efficiency filtration where bulk flash pasteurization is performed.

Process	Dry Bulb, °F	rh, %
ELECTRICAL PRODUCTS		
Electronics and x-ray		
Coil and transformer winding	72	15
Semiconductor assembly	68	40 to 50
Electrical instruments		
Manufacture and laboratory	70	50 to 55
Thermostat assembly and calibration	75	50 to 55
Humidistat assembly and calibration	75	50 to 55
Small mechanisms		
Close tolerance assembly	72*	40 to 45
Meter assembly and test	75	60 to 63
Switchgear		
Fuse and cutout assembly	73	50
Capacitor winding	73	50
Paper storage	73	50
Conductor wrapping with yarn	75	65 to 70
Lightning arrester assembly	68	20 to 40
Thermal circuit breakers assembly and test	75	30 to 60
High-voltage transformer repair	79	5
Water wheel generators		
Thrust runner lapping	70	30 to 50
Rectifiers		
Processing selenium and copper oxide plates	73	30 to 40

*Temperature to be held constant.

Dust control is essential in these processes. Minimum control requires medium-efficiency filters. Degree of filtration depends on the type of function in the area. Smaller tolerances and miniature components suggest high-efficiency particulate air (HEPA) filters.

Process	Dry Bulb, °F	rh, %
FUR		
Drying	110	
Shock treatment	18 to 20	
Storage	40 to 50	55 to 65

Shock treatment or eradication of any insect infestations requires lowering the temperature to 18 to 20°F for 3 to 4 days, then raising it to 60 to 70°F for 2 days, then lowering it again for 2 days and raising it to the storage temperature.

Furs remain pliable, oxidation is reduced, and color and luster are preserved when stored at 40 to 50°F.

Humidity control is required to prevent mold growth (which is prevalent with humidities above 80%) and hair splitting (which is common with humidities lower than 55%).

Process	Dry Bulb, °F	rh, %
GUM		
Manufacturing	77	33
Rolling	68	63
Stripping	72	53
Breaking	73	47
Wrapping	73	58

Process	Dry Bulb, °F	rh, %
LEATHER		
Drying	68 to 125	75
Storage, winter room temperature	50 to 60	40 to 60

After leather is moistened in preparation for rolling and stretching, it is placed in an atmosphere of room temperature and 95% relative humidity.

Leather is usually stored in warehouses without temperature and humidity control. However, it is necessary to keep humidity sufficiently low to prevent mildew. Medium-efficiency particulate air filtration is recommended for fine finish.

Process	Dry Bulb, °F	rh, %
FLOOR COVERING		
Linoleum		
Mechanical oxidizing of linseed oil*	90 to 100	
Printing	80	
Stoving process	160 to 250	

*Precise temperature control required.

Medium-efficiency particulate air filtration is recommended for the stoving process.

Process	Dry Bulb, °F	rh, %
LENSES (OPTICAL)		
Fusing	75	45
Grinding	80	80

Table 1   Temperatures and Humidities for Industrial Air Conditioning (*Continued*)

Process	Dry Bulb, °F	rh, %	Process	Dry Bulb, °F	rh, %
MATCHES			**PLASTICS**		
Manufacture	72 to 73	50	Manufacturing areas		
Drying	70 to 75	60	Thermosetting molding compounds	80	25 to 30
Storage	60 to 63	50	Cellophane wrapping	75 to 80	45 to 65

Water evaporates with the setting of the glue. The amount of water evaporated is 18 to 20 lb per million matches. The match machine turns out about 750,000 matches per hour.

In manufacturing areas where plastic is exposed in the liquid state or molded, high-efficiency particulate air filters may be required. Dust collection and fume control are essential.

Process	Dry Bulb, °F	rh, %	Process	Dry Bulb, °F	rh, %
PAINT APPLICATION			**PLYWOOD**		
Lacquers: Baking	300 to 360		Hot pressing (resin)	90	60
Oil paints: Paint spraying	60 to 90	80	Cold pressing	90	15 to 25

The required air filtration efficiency depends on the painting process. On fine finishes, such as car bodies, high-efficiency particulate air filters are required for the outdoor air supply. Other products may require only low- or medium-efficiency filters.

Makeup air must be preheated. Spray booths must have 100 fpm face velocity if spraying is performed by humans; lower air quantities can be used if robots perform spraying. Ovens must have air exhausted to maintain fumes below explosive concentration. Equipment must be explosion-proof. Exhaust must be cleaned by filtration and solvents reclaimed or scrubbed.

Process	Dry Bulb, °F	rh, %
RUBBER-DIPPED GOODS		
Manufacture	90	
Cementing	80	25 to 30*
Dipping surgical articles	75 to 80	25 to 30*
Storage prior to manufacture	60 to 75	40 to 50*
Testing laboratory	73	50*

*Dew point of air must be below evaporation temperature of solvent.

Solvents used in manufacturing processes are often explosive and toxic, requiring positive ventilation. Volume manufacturers usually install a solvent-recovery system for area exhaust systems.

Process	Dry Bulb, °F	rh, %
PHOTO STUDIO		
Dressing room	72 to 74	40 to 50
Studio (camera room)	72 to 74	40 to 50
Film darkroom	70 to 72	45 to 55
Print darkroom	70 to 72	45 to 55
Drying room	90 to 100	35 to 45
Finishing room	72 to 75	40 to 55
Storage room (black and white film and paper)	72 to 75	40 to 60
Storage room (color film and paper)	40 to 50	40 to 50
Motion picture studio	72	40 to 55

Process	Dry Bulb, °F	rh, %
TEA		
Packaging	65	65

Ideal moisture content is 5 to 6% for quality and mass. Low-limit moisture content for quality is 4%.

Process	Dry Bulb, °F	rh, %
TOBACCO		
Cigar and cigarette making	70 to 75	55 to 65*
Softening	90	85 to 88
Stemming and stripping	75 to 85	70 to 75
Packing and shipping	73 to 75	65
Filler tobacco casing and conditioning	75	75
Filter tobacco storage and preparation	77	70
Wrapper tobacco storage and conditioning	75	75

*Relative humidity fairly constant with range as set by cigarette machine.

Before stripping, tobacco undergoes a softening operation.

The above data pertain to average conditions. In some color processes, elevated temperatures as high as 105°F are used, and a higher room temperature is required.

Conversely, ideal storage conditions for color materials necessitate refrigerated or deep-freeze temperatures to ensure quality and color balance when long storage times are anticipated.

Heat liberated during printing, enlarging, and drying processes is removed through an independent exhaust system, which also serves the lamp houses and dryer hoods. All areas except finished film storage require a minimum of medium-efficiency particulate air filters.

paper, wood, leather, and tobacco. Moisture in vegetable and animal materials (and some minerals) reaches equilibrium with the moisture in the surrounding air by **regain** (the percentage of absorbed moisture in a material compared to that material's bone-dry mass). For example, if a material sample with a mass of 5.5 lb has a mass of only 5 lb after thorough drying under standard conditions of 220 to 230°F, the mass of absorbed moisture is 0.5 lb, 10% of the sample's bone-dry mass. Therefore, the regain is 10%.

Table 2 lists typical regain values for materials at 75°F in equilibrium at various relative humidities. Temperature change affects the rate of absorption or drying, which generally varies with the thickness, density, and nature of the material. Sudden temperature changes cause slight change in regain even with fixed relative humidity, but the major change occurs as a function of relative humidity.

Hygroscopic materials deliver sensible heat to the air in an amount equal to the latent heat of the absorbed moisture. The amount of heat liberated should be added to the cooling load if it is significant, but it is usually quite small. Manufacturing economy

requires regain to be maintained at a level suitable for rapid and satisfactory manipulation. Uniform relative humidity allows high-speed machinery to operate efficiently.

Some materials may be exposed to the required humidity during manufacturing or processing, others may be treated separately after conditioning and drying. Conditioning removes or adds hygroscopic moisture. Drying removes both hygroscopic moisture and free moisture in excess of that in equilibrium. Drying and conditioning can be combined to remove moisture and accurately regulate the final moisture content in products such as tobacco and textiles. Conditioning or drying is frequently a continuous process in which the material is conveyed through a tunnel and subjected to controlled atmospheric conditions. For more detail, see Chapter 22 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*.

Corrosion, Rust, and Abrasion

In manufacturing metal products, temperature and relative humidity need to be kept sufficiently low to prevent hands from sweating, thus protecting the finished article from fingerprints,

Table 2   Regain of Hygroscopic Materials*

Classification	Material	Description	Relative Humidity								
			10	20	30	40	50	60	70	80	90
Natural	Cotton	Sea island—roving	2.5	3.7	4.6	5.5	6.6	7.9	9.5	11.5	14.1
textile	Cotton	American—cloth	2.6	3.7	4.4	5.2	5.9	6.8	8.1	10.0	14.3
fibers	Cotton	Absorbent	4.8	9.0	12.5	15.7	18.5	20.8	22.8	24.3	25.8
	Wool	Australian merino—skein	4.7	7.0	8.9	10.8	12.8	14.9	17.2	19.9	23.4
	Silk	Raw chevennes—skein	3.2	5.5	6.9	8.0	8.9	10.2	11.9	14.3	18.3
	Linen	Table cloth	1.9	2.9	3.6	4.3	5.1	6.1	7.0	8.4	10.2
	Linen	Dry spun—yarn	3.6	5.4	6.5	7.3	8.1	8.9	9.8	11.2	13.8
	Jute	Average of several grades	3.1	5.2	6.9	8.5	10.2	12.2	14.4	17.1	20.2
	Hemp	Manila and sisal rope	2.7	4.7	6.0	7.2	8.5	9.9	11.6	13.6	15.7
Rayons	Viscose nitrocellulose	Average skein	4.0	5.7	6.8	7.9	9.2	10.8	12.4	14.2	16.0
	Cuprammonium cellulose acetate		0.8	1.1	1.4	1.9	2.4	3.0	3.6	4.3	5.3
Paper	M.F. newsprint	Wood pulp—24% ash	2.1	3.2	4.0	4.7	5.3	6.1	7.2	8.7	10.6
	H.M.F. writing	Wood pulp—3% ash	3.0	4.2	5.2	6.2	7.2	8.3	9.9	11.9	14.2
	White bond	Rag—1% ash	2.4	3.7	4.7	5.5	6.5	7.5	8.8	10.8	13.2
	Comm. ledger	75% rag—1% ash	3.2	4.2	5.0	5.6	6.2	6.9	8.1	10.3	13.9
	Kraft wrapping	Coniferous	3.2	4.6	5.7	6.6	7.6	8.9	10.5	12.6	14.9
Miscellaneous	Leather	Sole oak—tanned	5.0	8.5	11.2	13.6	16.0	18.3	20.6	24.0	29.2
organic	Catgut	Racquet strings	4.6	7.2	8.6	10.2	12.0	14.3	17.3	19.8	21.7
materials	Glue	Hide	3.4	4.8	5.8	6.6	7.6	9.0	10.7	11.8	12.5
	Rubber	Solid tires	0.11	0.21	0.32	0.44	0.54	0.66	0.76	0.88	0.99
	Wood	Timber (average)	3.0	4.4	5.9	7.6	9.3	11.3	14.0	17.5	22.0
	Soap	White	1.9	3.8	5.7	7.6	10.0	12.9	16.1	19.8	23.8
	Tobacco	Cigarette	5.4	8.6	11.0	13.3	16.0	19.5	25.0	33.5	50.0
Miscellaneous	Asbestos fiber	Finely divided	0.16	0.24	0.26	0.32	0.41	0.51	0.62	0.73	0.84
inorganic	Silica gel		5.7	9.8	12.7	15.2	17.2	18.8	20.2	21.5	22.6
materials	Domestic coke		0.20	0.40	0.61	0.81	1.03	1.24	1.46	1.67	1.89
	Activated charcoal	Steam activated	7.1	14.3	22.8	26.2	28.3	29.2	30.0	31.1	32.7
	Sulfuric acid		33.0	41.0	47.5	52.5	57.0	61.5	67.0	73.5	82.5

*Moisture content expressed in percent of dry mass of the substance at various relative humidities, temperature 75°F.

tarnish, and/or etching. Salt and acid in perspiration can cause corrosion and rust in a few hours. Manufacture of polished surfaces and of steel-belted radial tires usually requires medium-efficiency to HEPA filtering to prevent surface abrasion.

Air Cleanliness

Each application must be evaluated to determine the filtration needed to counter the adverse effects on the product or process of dust particles, airborne bacteria, smoke, spores, pollen, and radioactive particles. These effects include chemically altering production material, spoiling perishable goods, and clogging small openings in precision machinery. See Chapter 24 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment* for details.

Static Electricity

Humidity can reduce static electricity in processing light materials such as textile fibers and paper and where potentially explosive atmospheres or materials are present. Static electricity is often detrimental to processing and extremely dangerous in explosive atmospheres. Static electric charges are minimized when relative humidity is above 35%. Room relative humidity may need to be maintained at 65% or higher because machinery heat raises the machine ambient temperature well above the room temperature at which the relative humidity is normally measured.

EMPLOYEE REQUIREMENTS

Space conditions required by health and safety standards to avoid excess exposure to high temperatures and airborne contaminants are often established by the American Conference of Governmental Industrial Hygienists (ACGIH). In the United States, the National Institute of Occupational Safety and Health (NIOSH) does research and recommends guidelines for workplace environments. The Occupational Safety and Health Administration (OSHA) sets standards based on these guidelines, with enforcement usually assigned to a corresponding state agency.

Standards for safe levels of contaminants in the work environment or in air exhausted from facilities do not cover everything that may be encountered. Minimum safety standards and design criteria are available from U.S. Department of Health agencies such as the National Institute of Health, National Cancer Institute, and Public Health Service. The U.S. Department of Energy and Nuclear Regulatory Commission establish standards for radioactive substances.

Thermal Control Levels

Industrial plants are usually designed for an internal temperature of 60 to 90°F and a maximum of 60% rh. Tighter controls are often dictated by the specific operations and processes located in the building. ACGIH (2007) established guidelines to evaluate high temperature and humidity levels in terms of heat stress (Dukes-Dobos and Henschel 1971). See Chapter 8 of the 2005 *ASHRAE Handbook—Fundamentals* for a more detailed analysis of work rate, air velocity, rest, and the effects of radiant heat.

Temperature control becomes tighter and more specific if personnel comfort rather than avoidance of heat stress becomes the criterion. Nearly sedentary workers prefer a winter temperature of 72°F and a summer temperature of 78°F at a maximum of 60% rh. Workers at a high rate of activity prefer 65°F; they are less sensitive to temperature changes and can be cooled by increasing the air velocity. ASHRAE *Standard* 55 provides more detailed information.

Contamination Control Levels

Toxic and/or hazardous materials are present in many industrial plants and laboratories. Gases and vapors are found near acid baths and tanks holding process chemicals. Plating operations, spraying, mixing, abrasive cleaning, and other processes generate dust, fumes, and mists. Many animal and laboratory procedures (e.g., grinding, blending, sonication, weighing) generate aerosols. Air-conditioning and ventilation systems must minimize exposure to these materials. When airborne, these materials greatly expand their range and potential for affecting more employees. Chapter 12 of the 2005 *ASHRAE Handbook—Fundamentals*, OSHA requirements, and ACGIH (2007) give guidance on the health impact of various materials.

Concentrations of gaseous flammable substances must also be kept below explosive limits. Acceptable concentrations of these substances are a maximum of 25% of the lower explosive limit. Chapter 12 of the 2005 *ASHRAE Handbook—Fundamentals* provides data on flammable limits and their means of control.

Instruments are available to measure concentrations of common gases and vapors, but specific monitoring requirements and methods must be developed for uncommon ones.

DESIGN CONSIDERATIONS

Required environmental conditions for equipment, process and personnel comfort must be known before selecting HVAC equipment. The engineer and owner jointly establish design criteria, including the space-by-space environment in the facilities, process heat loads and exhaust requirements, heat and cooling energy recovery, load factors and equipment diversity, lighting, cleanliness, etc. Consideration should be given to the method of separating dirty processes from areas that require progressively cleaner air.

Insulation should be evaluated for initial cost and operating and energy cost savings. When high levels of moisture are required within the building, the air-conditioning and structural envelope must prevent unwanted condensation and ensure a high-quality product. Condensation can be prevented by eliminating thermal short circuits, installing proper insulation, and using vapor barriers. See Chapters 23 and 24 of the 2005 *ASHRAE Handbook—Fundamentals* for further details.

Personnel engaged in some industrial processes may be subject to a wide range of activity levels for which a broad range of temperatures and humidities are desirable. Chapter 8 of the 2005 *ASHRAE Handbook—Fundamentals* addresses recommended indoor conditions for a variety of activity levels.

If layout and construction drawings are not available, a complete survey of existing premises and a checklist for proposed facilities are necessary (Table 3).

New industrial buildings are typically single-story with a flat roof and ample height to distribute air and utilities without interfering with process operations. Fluorescent fixtures are commonly mounted at heights up to 12 ft, high output fluorescent fixtures up to 20 ft, and high pressure sodium or metal halide fixtures above 20 ft. Lighting design considers light quality, diffusion, room size, mounting height, and economics. Illumination levels should conform to recommendations of the Illuminating Engineering Society of North America.

Air-conditioning systems can be located on the roof of the building. Air intakes should not be located too close to loading docks or other sources of contamination. (See the section on Air Filtration Systems.) HVAC system installation must be coordinated with other systems and equipment that compete for space at the top of the building, such as fire sprinklers, lighting, cranes, structural elements, etc.

Operations in the building must also be considered: some require close control of temperature, humidity, and/or contaminants. A

Table 3   Facilities Checklist

Construction
 1. Single or multistory
 2. Type and location of doors, windows, crack lengths
 3. Structural design live loads
 4. Floor construction
 5. Exposed wall materials
 6. Roof materials and color
 7. Insulation type and thicknesses
 8. Location of existing exhaust equipment
 9. Building orientation

Use of Building
 1. Product needs
 2. Surface cleanliness; acceptable airborne contamination level
 3. Process equipment: type, location, and exhaust requirements
 4. Personnel needs, temperature levels, required activity levels, and special workplace requirements
 5. Floor area occupied by machines and materials
 6. Clearance above floor required for material-handling equipment, piping, lights, or air distribution systems
 7. Unusual occurrences and their frequency, such as large cold or hot masses of material moved inside
 8. Frequency and length of time doors open for loading or unloading
 9. Lighting, location, type, and capacity
 10. Acoustical levels
 11. Machinery loads, such as electric motors (size, diversity), large latent loads, or radiant loads from furnaces and ovens
 12. Potential for temperature stratification

Design Conditions
 1. Design temperatures—indoor and outdoor dry and wet bulb
 2. Altitude
 3. Wind velocity
 4. Makeup air required
 5. Indoor temperature and allowable variance
 6. Indoor relative humidity and allowable variance
 7. Indoor air quality definition and allowable variance
 8. Outdoor temperature occurrence frequencies
 9. Operational periods: one, two, or three
 10. Waste heat availability and energy conservation
 11. Pressurization required
 12. Mass loads from the energy release of productive materials

Code and Insurance Requirements
 1. State and local code requirements for ventilation rates, etc.
 2. Occupational health and safety requirements
 3. Insuring agency requirements

Utilities Available and Required
 1. Gas, oil, compressed air (pressure), electricity (characteristics), steam (pressure), water (pressure), wastewater, interior and site drainage
 2. Rate structures for each utility
 3. Potable water

schedule of operations is helpful in determining heating and cooling loads.

LOAD CALCULATIONS

Table 1 and specific product chapters of this Handbook discuss product requirements. Chapter 30 of the 2005 *ASHRAE Handbook—Fundamentals* provides appropriate heating and cooling load calculation techniques.

Solar and Transmission

The roof load is usually the largest solar load on the envelope. Solar loads on walls are often insignificant particularly because

modern factory buildings tend to be windowless. Insulating building walls and roof almost always benefits HVAC cost and performance.

Internal Heat Generation

Internal heat generated by equipment and processes, as well as products, lighting, people and utilities, may satisfy heating load requirements. Understanding equipment operating schedules allows an appropriate diversity factor to be applied to the actual power consumption. Using connected loads may greatly oversize the system. Processes tend to operate continuously but may be shut down on weekends or at night. Heating to some minimal level without equipment and/or process load should be considered.

The latent load in most industrial facilities is minimal, with people and outside air being the primary contributors. Some processes and products do generate a latent load. They need to be understood because this latent load can dominate the HVAC system design. Moisture condensation on cold surfaces must be managed when the latent load becomes very large.

Stratification Effect

The cooling load may be dramatically reduced in a work space that takes advantage of temperature stratification. A stagnant blanket of warm air directly under the roof will have little effect on occupants or equipment as long as it remains undisturbed. Heat sources near the stagnant air will have little effect on the cooling load. When the ceiling or roof is high, 20 to 60% of the heat energy rises out of the cooling zone, depending on building construction and the temperature of heat sources. Switching to a return air location near the roof could be cost effective, because it takes advantage of higher temperatures at the roof.

Supply and return air ducts should be installed as low as practical to avoid mixing the warm boundary layers in cooling mode. The location of supply air diffusers generally establishes the stratified air boundary. Spaces with a low occupant-to-floor-area ratio adapt well to using low quantities of supply air with spot cooling for personnel.

Makeup Air

Makeup air provides ventilation and building pressurization. It must be filtered and conditioned to blend with return air and then distributed to the conditioned space. The quantity of makeup air must exceed that of the exhaust air to positively pressurize the building. Makeup air quantity may be varied to accommodate an exhaust system with intermittently operating elements. Heat and cooling recovery from the exhaust airstream can substantially reduce the outside air load.

Processes requiring an extensive amount of exhaust air should ideally be placed in an area of the plant provided with minimal heating and no refrigerated air conditioning. Ventilation air may be required to reduce the quantity of health-threatening fumes, airborne bacteria, or radioactive particles. Minimum ventilation rates must meet the requirements of ASHRAE *Standard* 62.1.

Economizers can take advantage of ambient conditions and possibly satisfy HVAC loads without added heating or cooling for much of the year.

Fan Heat

Heat is generated by fans used to move and pressurize the air. This heat is not felt by the occupants but does add to the cooling load. The discharge air temperature of a draw-through cooling arrangement requires cooler air to the fan to accommodate the temperature increase of air passing through the fan. The increase is more significant in systems with higher discharge air pressures.

SYSTEM AND EQUIPMENT SELECTION

Industrial air-conditioning equipment includes heating and cooling sources, air-handling and air-conditioning apparatus, filters, and an air distribution system. Components should be selected and the system designed for long life with low maintenance and operating costs to provide low life-cycle cost.

Systems may consist of the following:

- Heating-only in cool climates, where ventilation air provides comfort for workers
- Air washer systems, where high humidities are desired and where the climate requires cooling
- Heating and evaporative cooling, where the climate is dry
- Heating and mechanical cooling, where temperature and humidity control are required and other means of cooling are insufficient

All systems include air filtration appropriate to the contaminant control required.

Careful evaluation should determine zones that require control, especially in large, high-bay areas where the occupied zone is a small portion of space volume. ASHRAE *Standard* 55 defines the occupied zones as 3 to 72 in. high and more than 24 in. from the walls.

HEATING SYSTEMS

Floor Heating

Floor heating is often desirable in industrial buildings, particularly in large, high-bay buildings, garages, and assembly areas where workers must be near the floor, or where large or fluctuating outside air loads make maintaining ambient temperature difficult.

Floors may be tempered to 65 or 70°F by embedded hydronic systems, electrical resistance cables, or warm air ducts as an auxiliary to the main heating system. Heating elements may be buried deep in the floor (6 to 18 in.) to allow slab warm-up at off-peak times, thus using the floor mass as heat storage to save energy during periods of high use.

Floor heating may be the primary or sole heating means, but floor temperatures above 85°F are uncomfortable, so such use should be limited to small, well-insulated spaces.

Unit and Ducted Heaters

Gas, oil, electric, hot-water, or steam-fired unit heaters with centrifugal or propeller fans are used for spot heating areas or are arranged in multiples for heating an entire building. Temperatures can be varied by individual thermostatic control. Unit heaters should be located so that the discharge (throw) will reach the floor adjacent to and parallel with the outside wall, and spaced to produce a ring of warm air moving peripherally around the building. In industrial buildings with heat-producing processes, heat tends to stratify in high-bay areas. In large buildings, additional heaters should be placed in the interior so that their discharge reaches the floor to reduce stratification. Downward-discharge unit heaters in high bays and large areas may have a revolving discharge. Gas- and oil-fired unit heaters should not be used where corrosive vapors are present.

Ducted heaters include large direct- or indirect-fired heaters, door heaters, and heating and ventilating units. They usually have centrifugal fans. Direct-fired gas heaters, in which the gas burns in the air being supplied to the space, may be used for makeup air heating because they are self-venting, thus controlling the products of combustion.

Unit heaters and makeup air heaters commonly temper outside air that enters buildings through open doors. Mixing quickly brings the space temperature back to the desired setting after the door is closed. The makeup air heater should be applied as a door heater in buildings where the doors are large and open for extended periods, such as doors for large trucks or railroad cars. Unit heaters are also needed in buildings that have considerable leakage or a sizeable

negative pressure. These units help pressurize the door area, mix the incoming cold air, temper it, and quickly bring the area back to the desired temperature after the door is closed.

Door heating units that resemble a vestibule operate with airflow down across the opening and recirculated from the bottom, which help reduce cold drafts across the floor. These units are effective on high-usage doors under 10 ft tall. Additional information on heating is given in Chapter 31 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*.

Infrared Heaters

High-intensity gas, oil, or electric infrared heaters transfer heat directly to the occupants, equipment, and floor in the space without appreciably warming the air, though some air heating occurs by convection from objects heated by the infrared heaters. These heaters are classified as near- or far-infrared heaters, depending on how close the wavelengths they emit are to visible light. Near-infrared heaters emit a substantial amount of visible light.

Both vented and unvented gas-fired infrared heaters are available as individual radiant panels, or as a continuous radiant pipe with burners 15 to 30 ft apart and an exhaust vent fan at the end of the pipe. Unvented heaters require exhaust ventilation to remove flue products from the building and prevent moisture from collecting on the walls and ceiling. Insulation reduces the ventilation requirement.

Infrared heaters are common in the following applications:

- High-bay buildings, where heaters are usually mounted 10 to 30 ft above the floor, along outside walls, and tilted to direct maximum radiation to the floor. If the building is poorly insulated, the controlling thermostat should be shielded to avoid influence from the radiant effect of the walls and the cold walls.
- Semi-open and outside areas, where people can be comfortably heated directly and objects can be heated to avoid condensation.
- Loading docks, where snow and ice can be controlled by strategic placement of near-infrared heaters.

Additional information on both electric and gas infrared heating is given in Chapter 15 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*.

COOLING SYSTEMS

Common cooling systems include refrigeration equipment, evaporative coolers, and high-velocity ventilation air.

For manufacturing operations, particularly in heavy industry where mechanical cooling cannot be economically justified, evaporative cooling systems often provide good working conditions. If the operation requires heavy physical work, spot cooling by ventilation, evaporative coolers, or refrigerated air can be used. To minimize summer discomfort, high outside ventilation rates may be adequate in some hot-process areas. A mechanical air supply with good distribution is needed in all these operations.

Refrigerated Cooling Systems

The most commonly used refrigerated cooling systems are roof-mounted, direct-expansion packaged units. Larger systems may use chilled water distributed to air-handling units.

Central system condenser water rejects heat through a cooling tower. Refrigerated heat recovery is particularly advantageous in buildings with simultaneous need to heat exterior spaces and cool interior spaces.

Mechanical cooling equipment should be selected in multiple units. This enables the equipment to match its response to fluctuations in the load and to allow maintenance during off-peak operation periods. Packaged refrigeration equipment commonly uses positive-displacement (reciprocating, scroll, or screw) compressors with air-cooled condensers. When equipment is on the roof, the condensing temperature may be affected by warm ambient air, often 10 to 20°F higher than design outside air temperature. ASHRAE *Standard* 15

provides rules for the type and quantity of refrigerant in direct air-to-refrigerant exchangers.

For processes that require dew points below 50°F (e.g., pharmaceutical processing), desiccant-based systems should be considered.

Evaporative Cooling Systems

Evaporative cooling systems may be direct or indirect evaporative coolers or air washers. Evaporative coolers have water sprayed directly on wet surfaces through which air passes. Any excess water is drained off. An air washer recirculates water, and the air flows through a heavily misted area. Water atomized in the airstream evaporates, cooling the air. Refrigerated water simultaneously cools and dehumidifies the air. For spaces that require an air washer and high relative humidities (e.g., tobacco and textile processing areas), heat provided to the sump should provide sufficient energy for humidification beyond that from heat recovered in the return airstream.

Evaporative cooling conserves energy, particularly in mild weather. Air washers may control both temperature and humidity using refrigerated spray water and reheat coils. Temperature and humidity of the exit airstream may be controlled by varying the temperature of the chilled water and reheat coil and by varying the quantity of air passing through the reheat coil with a dew-point thermostat.

Ensure that accumulation of dust or lint does not clog the nozzles or evaporating pads of evaporative cooling systems. It may be necessary to filter air entering the evaporative cooler. Chemical treatment of the water may be necessary to prevent mineral build-up or biological growth on the pads or in the pans.

AIR FILTRATION SYSTEMS

Air filtration systems remove contaminants from the building supply or exhaust airstream. Supply air filtration at the equipment intake removes particulate contamination that may foul heat exchange surfaces, contaminant products, or present a health hazard to people, animals, or plants. Gaseous contaminants must sometimes be removed to prevent exposing personnel to odors or health-threatening fumes. Return air with a significant potential for carrying contaminants should be recirculated only if it can be filtered enough to minimize personnel exposure. Return air should be exhausted if monitoring and contaminant control cannot be ensured.

The supply filtration system usually includes collection media or a filter, a media-retaining device or filter frame, and a filter housing or plenum. The filter medium is the most important part of the system. A mat of randomly distributed small-diameter fibers is commonly used. For more on filtration systems, see Chapter 24 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*.

Exhaust Air Filtration Systems

Exhaust air systems are either (1) general systems that remove air from large spaces or (2) local systems that capture aerosols, heat, or gases at specific locations in a room and transport them so they can be collected, inactivated, and safely discharged to the atmosphere. Air in a general system usually requires minimal or no treatment before being discharged to the atmosphere. Air from local exhaust systems can sometimes be safely discharged to the atmosphere, but may require contaminant removal before being discharged. All emitted air must meet appropriate air quality standards. Chapters 28 and 29 of this volume and Chapter 25 of the 2004 *ASHRAE Handbook— HVAC Systems and Equipment* have more information on industrial ventilation and exhaust systems.

In exhaust air emission control, fabric-bag filters, glass-fiber filters, venturi scrubbers, and electrostatic precipitators all collect particles. Packed-bed or sieve towers can absorb toxic gases. Activated carbon columns or beds, often with oxidizing agents, are frequently used to absorb toxic or odorous organics and radioactive gases.

Outside air intakes should be carefully located to avoid recirculating contaminated exhaust air. Wind direction, building shape, and location of effluent source strongly influence concentration patterns.

Air patterns from wind flowing over buildings are discussed in Chapter 16 of the 2005 *ASHRAE Handbook—Fundamentals*. The leading edge of the roof interrupts smooth airflow, reducing air pressure at the roof and on the lee side. Exhaust air must be discharged through either a vertical stack terminating above the building turbulent air boundary or a shorter stack with a high enough discharge velocity to project the effluent through the air boundary into the undisturbed air passing over the building. The high discharge prevents fume damage to both the roof and roof-mounted equipment, and keeps fumes away from building air intakes. A high vertical stack is the safest, simplest solution to fume dispersal.

Contamination Control

In addition to maintaining thermal conditions, air-conditioning systems should control contaminant levels to provide a safe and healthy environment, good housekeeping, and quality control for the processes. Contaminants may be gases, fumes, mists, or airborne particulate matter; they may be produced by a process in the building or contained in the outside air.

Contamination can be controlled by preventing the release of aerosols or gases into the room and by diluting room air contaminants. If the process cannot be enclosed, it is best to capture aerosols and gases near their source with a local exhaust system that includes a hood or enclosure, ducts, fan, motor, and exhaust stack.

Dilution controls contamination in many applications but may not provide uniform safety for personnel. High local concentrations of contaminants can exist despite a high overall dilution rate.

EXHAUST SYSTEMS

An exhaust system draws a contaminant away from its source and removes it from the space. An exhaust hood surrounding the point of generation contains the contaminant as much as is practical. The contaminant is transported through ductwork from the space, cleaned as required, and exhausted to the atmosphere. The hood inlet air quantity is established by the velocities required to convey the airborne contaminant. Chapter 30 has more information on local exhaust systems.

Design values for average and minimum face velocities are a function of the characteristics of the most hazardous material the hood is expected to handle. Minimum values may be prescribed in codes for exhaust systems. Contaminants with greater mass may require higher face velocities for control. Design face velocities should be set carefully: too high a velocity can be as hazardous as one too low. Refer to ACGIH (2007) and ASHRAE *Standard* 110 for more information.

Properly sized ductwork keeps the contaminants flowing. This requires very high velocities for heavy materials. Selection of materials and construction of exhaust ductwork and fans depend on the nature of the contaminant, ambient temperature, lengths and arrangement of ducts, method of hood fan operation, and flame and smoke spread ratings.

Exhaust systems remove gases, vapors, or smokes from acids, alkalis, solvents, and oils. The following should be minimized:

- **Corrosion.** Commonly used reagents in laboratories include hydrochloric, sulfuric, and nitric acids (singly or in combination) and ammonium hydroxide. Commonly used organic chemicals include acetone, benzene, ether, petroleum, chloroform, carbon tetrachloride, and acetic acid.
- **Dissolution.** Coatings and plastics are subject to dissolving, particularly by solvent and oil fumes.
- **Melting.** Certain plastics and coatings at elevated hood operating temperatures can melt.

Low temperatures that cause condensation in ferrous metal ducts increase chemical destruction. Ducts are less subject to attack when runs are short and direct to the terminal discharge point. The longer the runs, the longer the exposure to fumes and the greater the condensation. Horizontal runs allow moisture to remain longer than

on vertical surfaces. Intermittent fan operation can contribute to longer periods of wetness than continuous operation. High loading of condensables in exhaust systems should be avoided by installing condensers or scrubbers as close to the source as possible.

OPERATION AND MAINTENANCE

All designs should allow ample room to clean, service, and replace any component quickly so that design conditions are affected as little as possible. Maintenance of refrigeration and heat rejection equipment is essential for proper performance without energy waste. Maintenance includes changing system filters periodically. Industrial applications are dirty, so proper selection of filters, careful installation to avoid air bypassing the filter, and prudent filter changing to prevent overloading and blowout are required. Dirt that lodges on the tips of forward-curved fan blades reduces air-handling capacity appreciably. Fan and motor bearings require lubrication, and fan belts need periodic inspection. Direct- and indirect-fired heaters should be inspected annually. Steam and hot-water heaters have fewer maintenance requirements than comparable equipment with gas or oil burners.

For system compatibility, water treatment is essential. Air washers and cooling towers should not be operated unless the water is properly treated.

HEAT RECOVERY AND ENERGY CONSERVATION

Process industry presents unique opportunities to recover heat from the exhaust airstream for use in preconditioning makeup air. Extreme care must be taken to ensure compatibility of heat exchanger components and materials with contaminants often found in exhaust streams. For example, brewery spaces are held between 35 and 50°F. Exhaust air passes over a heat recovery wheel to precondition outside makeup air, which in turn controls the level of carbon dioxide contamination. Coated aluminum heat recovery wheels can be subject to premature failure because of caustic cleaning materials conveyed in the exhaust system.

Additional consideration should be given to the assessment of risk associated with the heat recovery strategy. Frequently, downtime in large industrial facilities can exceed millions of dollars per hour. Costs associated with failure of a heat recovery device can easily overcome savings in energy costs if the result is a facility shutdown.

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CHAPTER 13

ENCLOSED VEHICULAR FACILITIES

THIS CHAPTER covers ventilation requirements for enclosed vehicular facilities. Enclosed vehicular facilities include any facility through which vehicles travel, are stored or repaired. The vehicles can be internal combustion engine or electric motor driven. The facilities included are tunnels, stations, garages, terminals, toll booths, and enclosed spaces for equipment maintenance.

The facility ventilation requirements can relate to climate and temperature control, contaminant level control, and emergency smoke/temperature management in road tunnels, rail tunnels, and subway stations, as well as in diesel locomotive facilities, enclosed parking structures, bus garages, bus terminals, and tollbooths.

Also covered are design approaches for various natural and mechanical ventilation systems, as well as applicable ventilation equipment.

The chapter is structured to address general tunnel issues first and then address the unique aspects of each enclosed vehicular facility type later in the chapter.

TUNNELS

Transport tunnels are unique enclosed vehicular facilities. They are the only enclosed vehicular facilities where vehicles travel at normal speeds, possibly carry cargo (unknown in road tunnels), and may include the traveling public (as passengers and/or motorists) within the facility during both normal and emergency operations. This combination of circumstances provides for some unique design approaches to both normal and emergency operation. A tunnel is a linear-configured facility, as opposed to most buildings, which are typically more rectangular. This concept comes into play when confronting the need to fight a fire within a tunnel. A tunnel cannot be compartmentalized as readily as a building, which means the fire can only be fought from within the actual fire zone, and therefore it is difficult to contain the fire.

Tunnel Ventilation Concepts

In the realm of tunnels there are three ventilation concepts widely used: normal, emergency, and temporary ventilation.

Normal ventilation is the ventilation required during normal operations of the facility. It may be used to control temperature, comfort, or level of pollutants within the facility during normal operations (under normal operating conditions), primarily to protect the health of the patrons.

Emergency ventilation is the ventilation required during an emergency in the facility. This is often due to a fire, but it can be any non-normal incident that requires unusual control of the environment within the facility. This includes control of smoke, exceedingly high levels of contaminants, high temperature, and any other abnormal environmental condition.

Temporary ventilation is needed during original construction or while maintenance-related work is being done in a tunnel, usually during non-operational hours. The temporary ventilation is typically

removed after construction or after the maintenance work is completed. Ventilation requirements for such temporary systems are specified by either state or local mining laws, industrial codes, or the U.S. Occupational Safety and Health Administration (OSHA) and are not addressed specifically in this chapter.

Tunnel Ventilation Systems

There are two categories of ventilation systems used in most tunnel facilities; natural and mechanical ventilation.

Natural Ventilation. Naturally ventilated facilities rely primarily on atmospheric conditions to maintain airflow and a satisfactory environment in the facility. The chief factor affecting the facility environment is the pressure differential created by differences in elevation, the ambient air temperature, or wind effects at the boundaries of the facility. Unfortunately, most of these factors do not reliably provide continuous and consistent results. If vehicles are moving through a tunnel type facility, the piston effect created by the moving vehicles may provide additional airflow.

Mechanical Ventilation. A tunnel that is long, has a heavy traffic flow, or experiences frequent adverse atmospheric conditions requires fan-based mechanical ventilation. Among the alternatives available for road tunnels are longitudinal and transverse ventilation.

Longitudinal Ventilation. This type of ventilation introduces or removes air from the facility at a limited number of points, primarily creating longitudinal airflow along the length of the facility. Longitudinal ventilation can be accomplished either by injection, using central fans, using jet fans mounted within the facility, or a combination of injection and extraction at intermediate points in the facility.

Transverse Ventilation. Transverse ventilation uses both a supply duct system and/or an exhaust duct system to uniformly distribute supply air and/or collect vitiated air throughout the length of the facility. The supply and exhaust ducts are served by a series of fixed fans usually housed in a ventilation building or structure.

Design Approach

General Air Quality Criteria. The air quality and corresponding ventilation system airflow requirements in all enclosed vehicular spaces are determined primarily by the type and quantity of contaminants that are generated or induced into the tunnel and the amount of ventilation needed to limit the high air temperatures or concentrations of these contaminants to acceptable levels for the specific time exposures.

The maximum allowable concentrations and levels of exposure for most contaminants are determined by the respective national governing agencies such as the U.S. Environmental Protection Agency (EPA), OSHA, the American Conference of Governmental Industrial Hygienists (ACGIH), etc.

The contaminant generators can be as varied as gasoline or diesel automobiles, diesel or compressed natural gas (CNG) buses and trucks, and diesel locomotives. Even heat generated by the air conditioning on electric trains stopped at stations and the pressure

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transients generated by rapid-transit moving trains can be considered contaminants, the effects of which need to be mitigated.

Design provisions also should be made to provide life safety conditions during a fire, when heat, smoke and a whole different set of contaminants may be generated. In designing for fires, the rate of burn or fire size should be taken into consideration. As a minimum, the design for fire life safety shall always conform to the specific standards or guidelines of the National Fire Protection Association (NFPA), as applicable. These standards and/or guidelines in the respective NFPA documents are often expressed in terms of tenable environment, which is defined in NFPA *Standard* 130 as "an environment that permits self-rescue of occupants for a specific period of time."

Wherever building codes apply, they should be adhered to, and close attention should be paid to the separation and pressurization requirements between adjacent facilities.

Specific design considerations, guidelines, and criteria are listed under each specific tunnel application covered by this chapter.

Technical Approach. The technical approach will differ depending on the type of facility; however, there are many similarities in the initial stages of the design process.

Determining the length and cross section for tunnels is an important first step. Establishing the dynamic clearance envelope for the facility is of extreme importance, especially for a tunnel, because all appurtenances, equipment, ductwork, jet fans, etc., have to be located outside the envelope, and this may eventually determine the type of ventilation system used.

Vehicle speeds, vehicle cross-sectional areas, and vehicle burn rates and fuel-carrying capacity are important considerations for road tunnels, as are train speeds, train headway, and rail car combustibility for rapid transit and railroad tunnels.

Types of cargo that will be allowed through the facility, and their respective burn rates, should be investigated to determine the ventilation rates and the best system for the application. Similarly, for railroad tunnels, it should be determined whether passenger or freight or both types of trains will be using the facility, and if the passenger trains will be powered by diesel/electric power or by electric traction power.

The manual calculations and resources for the emission and combustion data are given in the respective sections for each enclosed vehicular facility type. A first step in determining the order of magnitude for the ventilation rate required to control the movement of the heat and smoke layer generated by a fire in a tunnel is to apply the critical velocity criterion. This approach is described here, and can be used for all types of tunnel applications.

Critical Velocity. The simultaneous solution of Equations (1) and (2), by iteration, determines the critical velocity (Kennedy et al. 1996), which is the minimum steady-state velocity of ventilation air moving toward the fire needed to prevent backlayering:

$$V_C = K_1 K_G \left(\frac{gHq}{\rho c_p A T_F} \right)^{1/3} \qquad (1)$$

$$T_F = \left(\frac{q}{\rho c_p A V_C} \right) + T \qquad (2)$$

where

V_C = critical velocity, ft/s
T_F = average temperature of fire site gases, °R
K_1 = 0.606
K_G = grade factor (see Figure 1)
g = acceleration caused by gravity, ft/s^2
H = height of duct or tunnel at fire site, ft
q = heat that fire adds directly to air at fire site, Btu/s
ρ = average density of approach (upstream) air, lb/ft^3
c_p = specific heat of air, Btu/lb·°R
A = area perpendicular to flow, ft^2
T = temperature of approach air, °R

$K_g = 1 + 0.0374 \, (-\%)^{0.8}$
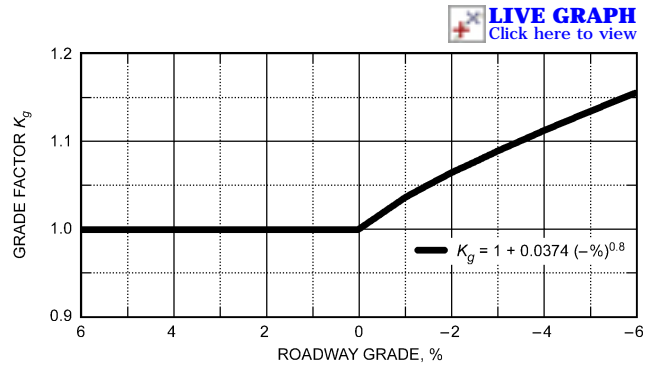
Fig. 1   Roadway Grade Factor

It is usual to study at least two and often more than two different ventilation schemes, each of which may or may not use the same type of ventilation system (longitudinal, transverse, etc.). Some types of systems, such as fully transverse, are almost exclusively used on road tunnels only.

When selecting the ventilation equipment and the number of fans and types of drives, consideration should be given to efficiency, reliability, and noise. Most of these equipment attributes are reflected in a life-cycle cost analysis of the alternatives.

If the effectiveness of the system to provide for fire life safety conditions is not evident from the manual analysis or one-dimensional computer models such as subway environment simulation (SES), the designer should investigate using one of the computational fluid dynamics (CFD) programs available for accurately determining the smoke and temperature distribution in both the steady state and transient conditions.

Computer Modeling and Simulation. The applicable NFPA standards for road tunnels and for railroad rapid transit tunnels require engineering analysis for tunnels greater than a certain length, to prove that the smoke and heat layer is controlled. Often the best way to show that the requirements are met is by use of a CFD program with post-processing capabilities that feed the results into another program capable of producing a still picture and/or an animated graphical representation of the results. All the commonly used computer programs and their specific capabilities are discussed in the following paragraphs.

SES. The SES computer program can be used to examine longitudinal airflow in a tunnel (DOT 1997a). SES, a one-dimensional network model, is the predominant worldwide tool used to evaluate longitudinal airflow in tunnels. This program contains a fire model that can determine how much longitudinal airflow is required to overcome backlayering and control smoke movement in a tunnel. The program is in the public domain, available from the Volpe National Transportation Systems Center in Cambridge, MA.

TUNVEN. This program solves coupled one-dimensional, steady-state tunnel aerodynamic and advection equations. It can predict quasi-steady-state longitudinal air velocities and concentrations of CO, NO_x, and total hydrocarbons along a road tunnel for a wide range of tunnel designs, traffic loads, and external ambient conditions.

The program can also be used to model all common road tunnel ventilation systems (i.e., natural, longitudinal, semitransverse, and transverse). The user needs to update emissions data for the calendar year of interest. The program is available from NTIS (1980).

CFD. Computational fluid dynamics software can model normal operating conditions in tunnels and predict the resulting contaminant concentration levels; however, the complexity of the modeling and amount of detail in the results may exceed that desired by the engineer. Computational fluid dynamics software is the design tool of choice to obtain an optimum design, because experimental methods are costly, complex, and yield limited information.

SOLVENT. SOLVENT is a specific CFD model developed as part of the Memorial Tunnel Fire Ventilation Test Program for simulating road tunnel fluid flow, heat transfer, and smoke transport. SOLVENT can be applied to all ventilation systems used in road tunnels, including those based on natural airflow. The program results have been validated against data from Massachusetts Highway Department and Federal Highway Authority (MHD/FHWA 1995).

FDS and Smokeview. FDS is a Computational Fluid Dynamics (CFD) model of fire-driven fluid flow. A separate application called Smokeview is used to visualize data output from FDS. These applications can also be configured to model pollutant levels outside the portals and around the exhaust stacks of tunnels. Both of these public domain programs are under active development and can be obtained from National Institute of Standards and Technology.

Other CFD programs, both commercially available and in the public domain, have been used to model fire scenarios in road and rapid transit tunnels, the list of which is too numerous to include here. The strengths and weaknesses of each program should be investigated beforehand, and validation of the results against experimental data or another equivalent program is encouraged.

Tunnel Fires

Occurrence. Fires occurring in tunnels are more difficult to deal with relative to those occurring in one of the other enclosed vehicular facilities, in a normal building, or in the open. In a tunnel, the ability to fight a fire is extremely complex, as access to the tunnel is difficult in the event of a fire. The fire cannot be fought from outside the tunnel, as can be done with a building; it must be fought from within the tunnel, many times in the same space where the fire is burning.

Fires occur in tunnels nowhere near as frequently as they occur in buildings; however, because of the unique nature of a tunnel fire, they are more difficult to suppress and extinguish and usually get more attention. There is a long list of tunnel fires; the most complete history of fires in tunnels exists for road tunnels, a listing of which is included in Table 1.

Table 1   List of Road Tunnel Fires

Year	Tunnel	Country	Length, ft	Fire Duration	Damage		
					People	Vehicles	Structure
1949	Holland	United States	8,365	4 h	66 injured	10 trucks 13 cars	Serious
1974	Mont Blanc	France/Italy	38,053	15 min	1 injured	—	—
1976	Crossing BP	France	1,411	1 h	12 injured	1 truck	Serious
1978	Velsen	Netherlands	2,526	1 h 20 min	5 dead 5 injured	4 trucks 2 cars	Serious
1979	Nihonzaka	Japan	6,708	159 h	7 dead 1 injured	127 trucks 46 cars	Serious
1980	Kajiwara	Japan	2,427	—	1 dead	2 trucks	Serious
1982	Caldecott	United States	3,372	2 h 40 min	7 dead 2 injured	3 trucks 1 bus 4 cars	Serious
1983	Pecorila Galleria	Italy	2,172	—	9 dead 22 injured	10 cars	Limited
1986	L'Arme	France	3,625	—	3 dead 5 injured	1 truck 4 cars	Limited
1987	Gumefens	Switzerland	1,125	2 h	2 dead	2 trucks 1 van	Slight
1990	Røldal	Norway	15,274	50 min	1 injured	—	Limited
1990	Mont Blanc	France/Italy	38,053	—	2 injured	1 truck	Limited
1993	Serra Ripoli	Italy	1,450	2 h 30 min	4 dead 4 injured	5 trucks 11 cars	Limited
1993	Hovden	Norway	4,232	1 h	5 injured	1 motor cycle 2 cars	Limited
1994	Huguenot	South Africa	12,839	1 h	1 dead 28 injured	1 bus	Serious
1995	Pfander	Austria	22,041	1 h	3 dead 4 injured	1 truck 1 van 1 car	Serious
1996	Isola delle Femmine	Italy	485	—	5 dead 20 injured	1 tanker 1 bus 18 cars	Serious
1999	Mont Blanc	France/Italy	38,053	—	39 dead	23 trucks 10 cars 1 motorcycle 2 fire engines	Serious
1999	Tauern	Austria	20,998	—	12 dead 49 injured	14 trucks 26 cars	Serious
2000	Seljestad	Norway	4,173	45 min	6 injured	1 truck 4 cars 1 MC	—
2001	Praponti	Italy	14,463	—	19 injured	—	Serious
2001	Gleinalm	Austria	27,293	—	5 dead 4 injured	—	—

Road Tunnels

A road tunnel is an enclosed vehicular facility with an operating roadway for motor vehicles passing through it. Road tunnels may be underwater (subaqueous), mountain, or urban, or may be created by air-right structures over a roadway or overbuilds of a roadway.

All road tunnels require ventilation to remove contaminants produced during normal engine operation. Normal ventilation may be provided by natural means, by traffic-induced piston effects, or by mechanical equipment. The method selected should be the most economical in both construction and operating costs.

Ventilation must also provide control of smoke and heated gases from a fire in the tunnel. Smoke flow control is needed to provide an environment suitable for both evacuation and rescue in the evacuation path. Emergency ventilation can be provided by natural means, by taking advantage of the buoyancy of smoke and hot gases, or by mechanical means.

Ventilation Modes. Three types of mechanical ventilation are typically considered for road tunnels: normal, emergency, and temporary, as discussed in the section on Tunnel Ventilation Concepts.

Ventilation Systems. Ventilation must dilute contaminants during normal tunnel operations and control smoke during emergency operations. Factors affecting ventilation system selection include tunnel length, cross section, and grade; surrounding environment; traffic volume, direction (i.e., unidirectional or bidirectional), and mix; and construction cost.

Natural and traffic-induced ventilation systems are adequate for relatively short tunnels, and for those with low traffic volume or density. Long, heavily traveled tunnels should have mechanical ventilation systems. The tunnel length at which this change takes effect is somewhere between 1200 and 2200 ft.

Natural Ventilation. Airflow through a naturally ventilated tunnel can be portal-to-portal (Figure 2A) or portal-to-shaft (Figure 2B). Portal-to-portal flow functions best with unidirectional traffic, which produces a consistent, positive airflow. In this case, air speed in the roadway area is relatively uniform, and the contaminant concentration increases to a maximum at the exit portal. Under adverse atmospheric conditions, air speed may decrease and contaminant concentration may increase, as shown by the dashed line in Figure 2A.

Introducing bidirectional traffic into such a tunnel further reduces longitudinal airflow and increases the average contaminant

A. PORTAL-TO-PORTAL

B. PORTAL-TO-SHAFT

Fig. 2 Natural Ventilation

concentration. The maximum contaminant level in a tunnel with bidirectional traffic will not likely occur at the portal, and will not necessarily occur at the midpoint of the tunnel.

A naturally ventilated tunnel with an intermediate shaft (Figure 2B) is better suited for bidirectional traffic; however, airflow through the shaft is also affected by adverse atmospheric conditions. The stack effect benefit of the shaft depends on air/rock temperatures, wind, and shaft height. Adding more than one shaft to a tunnel may be more of a disadvantage than an advantage, because a pocket of contaminated air can be trapped between the shafts.

Naturally ventilated tunnels over 1000 ft long require emergency ventilation to extract smoke and hot gases generated during a fire, as recommended by NFPA *Standard* 502. This standard also further recommends that tunnels between 800 and 1000 ft long require engineering analyses to determine the need for emergency ventilation. Emergency ventilation systems may also be used to remove stagnant contaminants during adverse atmospheric conditions. Because of the uncertainties of natural ventilation, especially the effects of adverse meteorological and operating conditions, reliance on natural ventilation to maintain carbon monoxide (CO) levels for tunnels over 800 ft long should be thoroughly evaluated. This is particularly important for tunnels with anticipated heavy or congested traffic. If natural ventilation is deemed inadequate, a mechanical system should be considered for normal operations.

Smoke from a fire in a tunnel with only natural ventilation is driven primarily by the buoyant effects of hot gases, and tends to flow upgrade. The steeper the grade, the faster the smoke moves, thus restricting the ability of motorists trapped between the incident and a portal at higher elevation to evacuate the tunnel safely. As shown in Table 2, the Massachusetts Highway Department and Federal Highway Administration (MHD/FHWA) (1995) demonstrated how smoke moves in a naturally ventilated tunnel.

Mechanical Ventilation. A tunnel that is long, has a heavy traffic flow, or experiences frequent adverse atmospheric conditions, requires fan-based mechanical ventilation. Options include longitudinal ventilation, semitransverse ventilation, and full transverse ventilation.

Longitudinal ventilation introduces or removes air from the tunnel at a limited number of points, creating longitudinal airflow along the roadway. Longitudinal ventilation can be accomplished either by injection, jet fan operation, or a combination of injection and extraction at intermediate points in the tunnel.

Injection longitudinal ventilation, frequently used in rail tunnels, uses centrally located fans to inject air into the tunnel through a high-velocity Saccardo nozzle, as shown in Figure 3A. This air injection, usually in the direction of traffic flow, induces additional longitudinal airflow. The Saccardo nozzle functions on the principle that a high-velocity air jet injected at an extremely small angle to the tunnel axis can induce a high-volume longitudinal airflow in the tunnel. The amount of induced flow depends primarily on the nozzle discharge velocity and angle of the nozzle. This type of ventilation is most effective with unidirectional traffic flow.

With injection longitudinal ventilation, air speed remains uniform throughout the tunnel, and the contaminant concentration increases from zero at the entrance to a maximum at the exit.
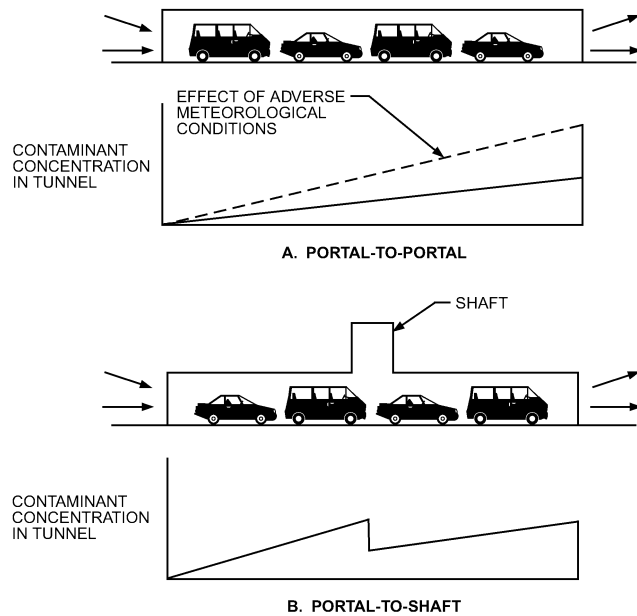
Table 2 Smoke Movement During Natural Ventilation Tests
(Memorial Tunnel Fire Ventilation Test Program)

Test No.	Fire Heat Release Rate, 10^6 Btu/h		Smoke Layer Begins Descent, min	Smoke Fills Tunnel Roadway, min	Peak Smoke Velocity, fpm
	Nominal	Peak			
501	68	99	3+	5	1200
502	170	194	1+	3	1600

Note: Tunnel grade is 3.2%.

A. WITH JET INJECTION

B. WITH ONE SHAFT

C. WITH TWO SHAFTS AND JET INJECTION

D. WITH JET FANS
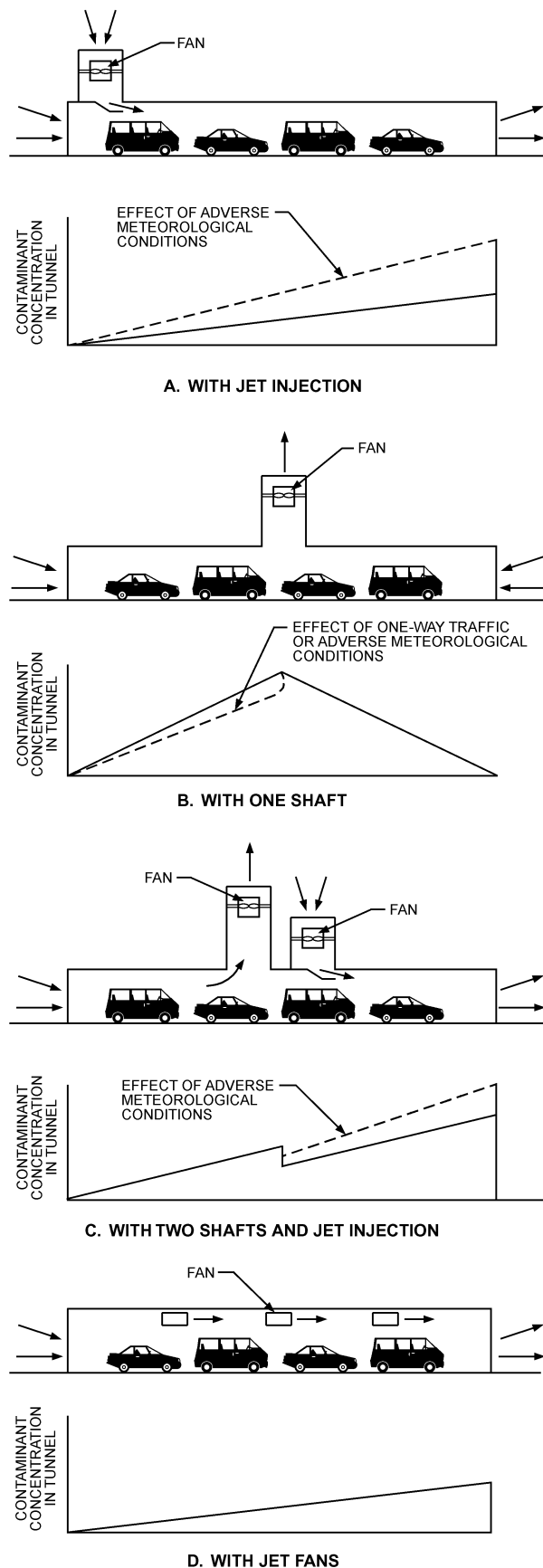
Fig. 3   Longitudinal Ventilation

Adverse atmospheric conditions can reduce system effectiveness. The contaminant level at the exit increases as airflow decreases or tunnel length increases.

Injection longitudinal ventilation, with supply at a limited number of tunnel locations, is economical because it requires the fewest fans, places the least operating burden on fans, and requires no distribution air ducts. As the length of the tunnel increases, however, disadvantages become apparent, such as excessive air velocities in the roadway and smoke being drawn the entire length of the roadway during an emergency.

Advantages of using a Saccardo nozzle-based longitudinal ventilation system over a jet fan-based system include the following:

- Reduced tunnel height
- Reduced number of moving parts to maintain
- Performing maintenance without impeding traffic flow
- Lower tunnel noise levels
- Higher fan efficiency
- Less chance of equipment being directly exposed to fire or hot gases

A longitudinal ventilation system with one fan shaft (Figure 3B) is similar to the naturally ventilated system with a shaft, except that it provides a positive stack effect. Bidirectional traffic in a tunnel ventilated this way causes peak contaminant concentration at the shaft. For unidirectional tunnels, contaminant levels become unbalanced.

Another form of longitudinal system has two shafts near the center of the tunnel: one for exhaust and one for supply (Figure 3C). In this arrangement, part of the air flowing in the roadway is replaced by the interaction at the shafts, which reduces the concentration of contaminants in the second half of the tunnel. This concept is only effective for tunnels with unidirectional traffic flow. Adverse wind conditions can reduce tunnel airflow by short-circuiting the flow of air from the supply fan shaft/injection port to the exhaust fan/shaft, which causes contaminant concentrations to increase in the second half of the tunnel.

Construction costs of two-shaft tunnels can be reduced if a single shaft with a dividing wall is constructed. However, this significantly increases the potential for short-circuited airflows from exhaust shaft to supply shaft; under these circumstances, the separation between exhaust shaft and intake shaft should be maximized.

Jet fan longitudinal ventilation has been installed in a number of tunnels worldwide. With this scheme, specially designed axial fans (jet fans) are mounted at the tunnel ceiling (Figure 3D). This system eliminates the space needed to house ventilation fans in a separate structure or ventilation building, but may require greater tunnel height or width to accommodate the jet fans so that they are outside of the tunnel's dynamic clearance envelope. This envelope, formed by the vertical and horizontal planes surrounding the roadway in a tunnel, defines the maximum limits of the predicted vertical and lateral movement of vehicles traveling on the roadway at design speed. As tunnel length increases, however, disadvantages become apparent, such as excessive air speed in the roadway and smoke being drawn the entire length of the roadway during an emergency.

Longitudinal ventilation is the most effective method of smoke control in a road tunnel with unidirectional traffic. A ventilation system must generate sufficient longitudinal air velocity to prevent **backlayering** of smoke (movement of smoke and hot gases against ventilation airflow in the tunnel roadway). The air velocity necessary to prevent backlayering over stalled or blocked motor vehicles is the minimum velocity needed for smoke control in a longitudinal ventilation system and is known as the **critical velocity**.

Semitransverse ventilation can be configured for supply or exhaust. This type of ventilation involves the uniform distribution (supply) and/or collection (exhaust) of air throughout the length of a road tunnel. Semitransverse ventilation is normally used in tunnels

up to about 7000 ft; beyond that length, tunnel air velocity near the portals becomes excessive.

Supply semitransverse ventilation in a tunnel with bidirectional traffic produces a uniform level of contaminants throughout, because air and vehicle exhaust gases enter the roadway area at the same uniform rate. With unidirectional traffic, additional airflow is generated by vehicle movement, thus reducing the contaminant level in the first half of the tunnel (Figure 4A).

Because tunnel airflow is fan-generated, this type of ventilation is not adversely affected by atmospheric conditions. Air flows the length of the tunnel in a duct with supply outlets spaced at predetermined distances. Fresh air is best introduced at vehicle exhaust pipe level to dilute exhaust gases immediately. The pressure differential between the duct and the roadway must be enough to counteract the effects of piston action and adverse atmospheric winds.

If a fire occurs in the tunnel, the supply air initially dilutes the smoke. Supply semitransverse ventilation should be operated in reverse mode for the emergency, so that fresh air enters through the portals and creates a respirable environment for both emergency egress and firefighter ingress. Therefore, a supply semitransverse ventilation system should preferably have a ceiling supply (in spite of the disadvantage during normal operations), and reversible fans, so that smoke can be drawn up to the ceiling during a tunnel fire.

Exhaust semitransverse ventilation (Figure 4B) in a tunnel with unidirectional traffic flow produces a maximum contaminant concentration at the exit portal. In a tunnel with bidirectional traffic flow, the maximum concentration of contaminants is located near the center of the tunnel. A combination supply and exhaust semitransverse system (Figure 4C) should be applied only in a unidirectional tunnel where air entering with the traffic stream is exhausted in the first half of the tunnel, and air supplied in the second half of the tunnel is exhausted through the exit portal.

In a fire emergency, both exhaust semitransverse ventilation and (reversed) semitransverse supply create a longitudinal air velocity in the tunnel roadway, and extract smoke and hot gases at uniform intervals.

Full transverse ventilation is used in extremely long tunnels and in tunnels with heavy traffic volume. It uses both a supply and an exhaust duct system to uniformly distribute supply air and collect vitiated air throughout the tunnel length (Figure 5). Because a tunnel with full transverse ventilation is typically long and served by more than one mechanical ventilation system, it is usually configured into ventilation zones, each served by a dedicated set of supply and exhaust fans. Each zone can be operated independently of adjacent zones, so the tunnel operator can change the direction of airflow in the tunnel by varying the level of operation of the supply and exhaust fans. This feature is important during fire emergencies.

With this ventilation system arrangement in balanced operation, air pressure along the roadway is uniform and there is no longitudinal airflow except that generated by the traffic piston effect, which tends to reduce contaminant levels. The pressure differential between the ducts and the roadway must be sufficient to ensure proper air distribution under all ventilation conditions.

During a fire, exhaust fans in the full transverse system should operate at the highest available capacity, and supply fans should operate at a somewhat lower capacity. This allows the stratified smoke layer (at the tunnel ceiling) to remain at that higher elevation and be extracted by the exhaust system without mixing, and allows fresh air to enter through the portals, which creates a respirable environment for both emergency egress and firefighter ingress.

In longer tunnels, individual ventilation zones should be able to control smoke flow so that the zone with traffic trapped behind a fire is provided with maximum supply and no exhaust, and the zone on the other side of the fire (where unimpeded traffic has continued onward) is provided with maximum exhaust and minimum or no supply.
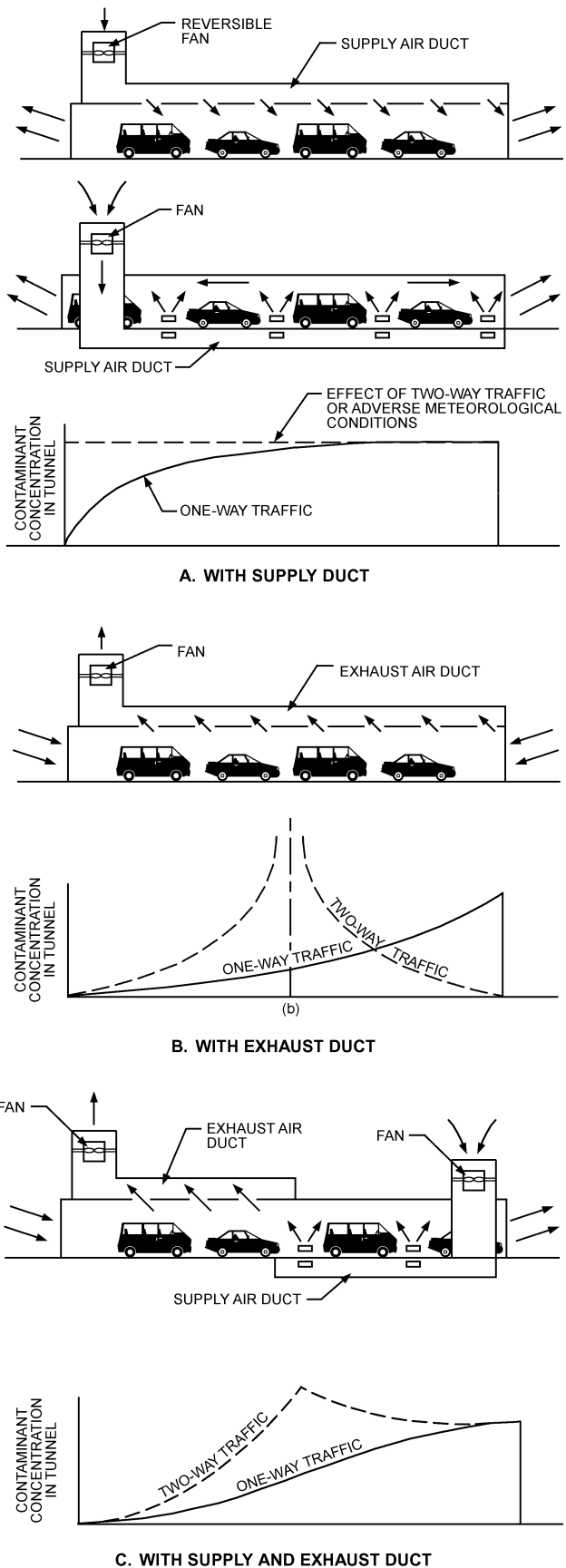
Fig. 4   Semitransverse Ventilation

Full-scale tests conducted by Fieldner et al. (1921) showed that supply air inlets should be at vehicle exhaust pipe level, and exhaust outlets should be in the tunnel ceiling for rapid dilution of exhaust gases under nonemergency operation. Depending on the number of traffic lanes and tunnel width, airflow can be concentrated on one side, or divided over two sides.

Other Ventilation Systems. There are many variations and combinations of the road tunnel ventilation systems described here. Most hybrid systems are configured to solve a particular problem faced in the development and planning of a specific tunnel, such as excessive air contaminants exiting at the portal(s). Figure 6 shows a hybrid system developed for a tunnel with a near-zero level of acceptable contaminant discharge at one portal. This system is essentially a semitransverse supply system, with a semitransverse exhaust system added in section 3. The exhaust system minimizes pollutant discharge at the exit portal, which is located near extremely sensitive environmental receptors.

Ventilation System Enhancements. **Single-point extraction** is an enhancement to a transverse system that adds large openings to the extraction (or exhaust) duct. These openings include devices that can be operated during a fire emergency to extract a large volume of smoke as close to the fire source as possible. Tests proved this concept effective in reducing air temperature and smoke volume in the tunnel. The size of the duct openings tested ranged from 100 to 300 ft^2 (MHD/FHWA 1995).

Oversized exhaust ports are simply expanded exhaust ports installed in the exhaust duct of a transverse or semitransverse ventilation system. Two methods are used to create this configuration. One is to install a damper with a fusible link; another uses a material that, when heated to a specific temperature, melts and opens the airway. Meltable materials showed only limited success in testing (MHD/FHWA 1995).

Normal Ventilation Air Quantities.

Contaminant Emission Rates. Because of the asphyxiate nature of the gas, CO is the exhaust gas constituent of greatest concern from spark-ignition engines. From compression-ignition (diesel) engines, the critical contaminants are nitrogen oxides (NO$_x$), such as nitric oxide (NO) and nitrogen dioxide (NO$_2$). Tests and operating experience indicate that, when CO level is properly diluted, other dangerous and objectionable exhaust by-products are also diluted to acceptable levels. An exception is the large amount of unburned hydrocarbons from vehicles with diesel engines; when diesel-engine vehicles exceed 15% of the traffic mix, visibility in the tunnel can become a serious concern. The section on Bus Terminals includes further information on diesel engine contaminants and their dilution.

Vehicle emissions of CO, NO$_x$, and hydrocarbons for any given calendar year can be predicted for cars and trucks operating in the United States by using the MOBILE models, developed and maintained by the U.S. Environmental Protection Agency. The current version is MOBILE6.2 (EPA 2004). In contaminant emission rate analyses, the following practices and assumptions may be implemented:

- CO emission rates are higher during acceleration and deceleration than at constant speed; this effect may be accounted for by adding a 10% safety factor to the computations.
- The effect of positive or negative grades up to 2% is usually neglected. Engineers should use judgment, or available data, in applying correction factors for positive grades greater than 2%.
- Traffic is assumed to move as a unit, with a constant space interval between vehicles, regardless of roadway grade.
- Average passenger vehicle dimensions may be assumed where specific vehicle data are unavailable.

Table 3 presents typical physical data for automobiles for use in normal ventilation air quantity analyses.

Allowable Carbon Monoxide. EPA's (1975) supplement to its *Guidelines for Review of Environmental Impact Statements* concerns the concentration of CO in tunnels. This supplement evolved into a design approach based on keeping CO concentration at or below 125 ppm, for a maximum 1 h exposure time, for tunnels located at or below an altitude of 3280 ft. In 1989, the EPA revised its recommendations for maximum CO levels in tunnels located at or below an altitude of 5000 ft to the following:

- A maximum of 120 ppm for 15 min exposure
- A maximum of 65 ppm for 30 min exposure
- A maximum of 45 ppm for 45 min exposure
- A maximum of 35 ppm for 60 min exposure

These guidelines do not apply to tunnels in operation before the adoption date.

At higher elevations, vehicle CO emissions are greatly increased, and human tolerance to CO exposure is reduced. For tunnels above 5000 ft, the engineer should consult with medical authorities to establish a proper design value for CO concentrations. Unless
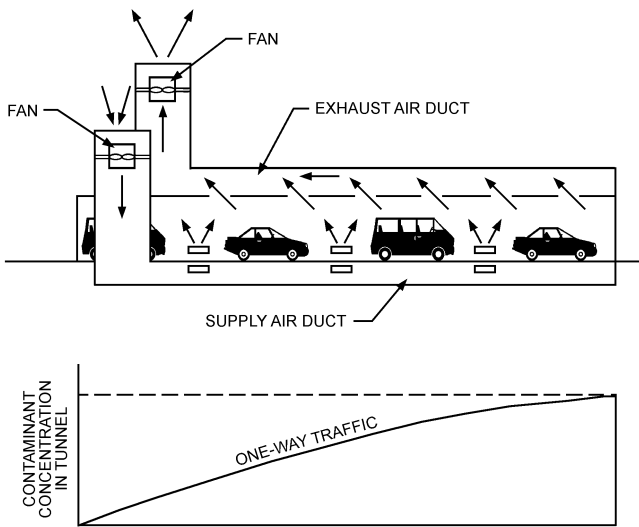
Fig. 5   Full Transverse Ventilation
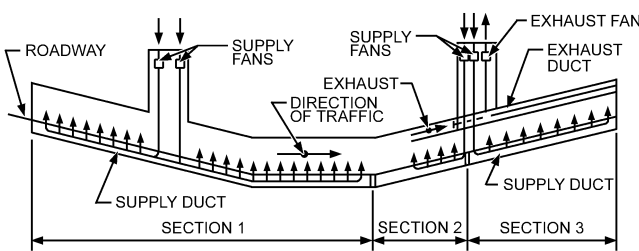
Fig. 6   Combined Ventilation System

Table 3   Average Dimensional Data for Automobiles Sold in the United States

Size/Class	Wheelbase, ft	Length, ft	Frontal Area, ft^2
Subcompact	8.0	14.0	17.3
Compact	9.0	15.9	19.8
Midsize	9.7	18.0	21.9
Large	10.0	18.5	22.4
Average	9.18	16.60	20.35

otherwise specified, the material in this chapter refers to tunnels at or below an altitude of 5000 ft.

Outdoor air standards and regulations such as those from the Occupational Safety and Health Administration (OSHA) and the American Conference of Governmental Industrial Hygienists (ACGIH) are discussed in the section on Bus Terminals.

Emergency Ventilation Air Quantities. A road tunnel ventilation system must be able to protect the traveling public during the most adverse and dangerous conditions (e.g., fires), as well as during normal conditions. Establishing the requisite air volume requirements is difficult because of many uncontrollable variables, such as the possible number of vehicle combinations and traffic situations that could occur during the lifetime of the facility.

For many years, the rule of thumb has been 100 cfm per lane-foot. The Memorial Tunnel Fire Ventilation Test Program (MHD/FHWA 1995) showed that this value is, in fact, a reasonable first pass at an emergency ventilation rate for a road tunnel.

Longitudinal flow, single-point extraction, and dilution are three primary methods for controlling smoke flow in a tunnel. Both longitudinal flow and single-point extraction depend on the ability of the emergency ventilation system to generate the critical velocity necessary to prevent backlayering.

Critical Velocity. The concept of critical velocity is addressed in the section on Design Approach, under Tunnels.

Fire Size. The fire size selected for design significantly affects the magnitude of the critical velocity needed to prevent backlayering. Table 4 provides typical fire size data for a selection of road tunnel vehicles.

Temperature. A fire in a tunnel significantly increases air temperature in the tunnel roadway and exhaust duct. Thus, both the tunnel structure and ventilation equipment are exposed to the high smoke/gas temperature. The air temperatures shown in Table 5 provide guidance in selecting design exposure temperatures for ventilation equipment.

Testing. The Memorial Tunnel Fire Ventilation Test Program was a full-scale test program conducted to evaluate the effectiveness of

various tunnel ventilation systems and ventilation airflow rates to control smoke from a fire (MHD/FHWA 1995). The results are useful in developing both emergency tunnel ventilation systems and emergency operational procedures.

Pressure Evaluation. Air pressure losses in tunnel ducts must be evaluated to compute the fan pressure and drive requirements. Fan selection should be based on total pressure across the fans, not on static pressure alone.

Fan total pressure FTP is defined by ASHRAE *Standard* 51/AMCA *Standard* 210 as the algebraic difference between the total pressures at fan discharge TP_2 and fan inlet TP_1, as shown in Figure 7. The fan velocity pressure FVP is defined as the pressure VP_2 corresponding to the bulk air velocity and air density at the fan discharge:

$$FVP = VP_2 \qquad (3)$$

Fan static pressure FSP is equal to the difference between fan total pressure and the fan velocity pressure:

$$FSP = FTP - FVP \qquad (4)$$

TP_2 must equal total pressure losses $\Delta TP_{2\text{-}3}$ in the discharge duct and exit pressure TP_3. Static pressure at the exit SP_3 is equal to zero.

$$TP_2 = \Delta TP_{2\text{-}3} + TP_3 = \Delta TP_{2\text{-}3} + VP_3 \qquad (5)$$

Likewise, total pressure at fan inlet TP_1 must equal the total pressure losses in the inlet duct and the inlet pressure:

$$TP_1 = TP_0 + \Delta TP_{0\text{-}1} \qquad (6)$$

Straight Ducts. Straight ducts in tunnel ventilation systems either (1) transport air, or (2) uniformly distribute (supply) or collect (exhaust) air. Several methods have been developed to predict pressure losses in a duct of constant cross-sectional area that uniformly distributes or collects air. The most widely used method was developed for the Holland Tunnel in New York (Singstad 1929). The following relationships, based on Singstad's work, give pressure losses at any point in a duct.

Total pressure for a **supply duct**

$$P_T = P_1 + \left(\frac{12\rho_a}{\rho_w g_c}\right)\left\{\frac{V_o^2}{2}\left[\frac{\alpha L Z^3}{3H} - (1-K)\frac{Z^2}{2}\right] + \frac{\beta L Z}{2H^3}\right\} \qquad (7)$$

Table 4 Typical Fire Size Data for Road Vehicles

Cause of Fire	Peak Fire Heat Release Rate, 10^6 Btu/h
Passenger car	17 to 34
Multiple passenger cars (2 to 4 Vehicles)	34 to 68
Bus	68 to 102
Heavy goods truck	239 to 682
Tanker[3]	682 to 1023

Source: NFPA *Standard* 502.
Notes:
1. The designer should consider rate of fire development (peak heat release rates may be reached within 10 min), number of vehicles that could be involved in fire, and potential for fire to spread from one vehicle to another.
2. Temperatures directly above fire can be expected to be as high as 1800 to 2550°F.
3. Flammable and combustible liquids for tanker fire design should include adequate drainage to limit area of pool fire and its duration. Heat release rate may be greater than listed if more than one vehicle is involved.

Table 5 Maximum Air Temperatures Experienced at Ventilation Fans During Memorial Tunnel Fire Ventilation Test Program

Nominal FHRR, 10^6 Btu/h	Temperature at Central Fans,[a] °F	Temperature at Jet Fans,[b] °F
68	225	450
170	255	700
340	325	1250

FHRR = Fire heat release rate
[a]Central fans located 700 ft from fire site.
[b]Jet fans located 170 ft downstream of fire site.

Fig. 7 Fan Total Pressure

Static pressure loss for an **exhaust duct**

$$P_S = P_1 + \left(\frac{12\rho_a}{\rho_w g_c}\right)\left\{\frac{V_o^2}{2}\left[\frac{\alpha LZ^3}{(3+c)H} + \frac{3Z^2}{(2+c)}\right] + \frac{\beta LZ}{2H^3(1+c)}\right\} \quad (8)$$

where

P_T = total pressure loss at any point in duct, in. of water
P_S = static pressure loss at any point in duct, in. of water
P_1 = pressure at last outlet, in. of water
ρ_a = density of air, lb/ft³
ρ_w = density of water, lb/ft³
V_o = velocity of air entering duct, ft/s
L = total length of duct, ft
X = distance from duct entrance to any location, ft
Z = $(L-X)/L$
H = hydraulic radius, ft
K = constant accounting for turbulence = 0.615
α = constant related to coefficient of friction for concrete = 0.0035
β = constant related to coefficient of friction for concrete
= 0.01433 ft⁴/s²
c = constant relating to turbulence of exhaust port
= 0.20 for exhaust rates less than 200 cfm per foot
= 0.25 for exhaust rates greater than 200 cfm per foot
g_c = gravitational constant = 32.2 lb_m·ft/lb_f·s²

The geometry of the exhaust air slot connection to the main duct is a concern in deriving the exhaust duct equation. The derivation is based on a 45° angle between the slot discharge and the main airstream axes. Variations in this angle can greatly affect the energy losses at the convergence from each exhaust slot, with total pressure losses for a 90° connection increasing by 50 to 100% over those associated with 45° angles (Haerter 1963).

For **distribution ducts** with sections that differ along their length, these equations may also be solved sequentially for each constant-area section, with transition losses considered at each change in section area. For a **transport duct** with constant cross-sectional area and constant air velocity, pressure losses are due to friction alone and can be computed using the standard expressions for losses in ducts and fittings (see Chapter 35 of the 2005 *ASHRAE Handbook—Fundamentals*).

Carbon Monoxide Analyzers and Recorders. Air quality in a tunnel should be monitored continuously at several key points. CO is the contaminant usually selected as the prime indicator of tunnel air quality. CO-analyzing instruments base their measurements on one of the following three processes:

- **Catalytic oxidation (metal oxide)** analysis offers reliability and stability at a moderate initial cost. Maintenance requirements are low, plus these instruments can be calibrated and serviced by maintenance personnel after only brief instruction.
- **Infrared** analysis is sensitive and responsive, but has a high initial cost. This instrument is precise but complex, and requires a highly trained technician for maintenance and servicing.
- **Electrochemical** analysis is precise; the units are compact, lightweight, and moderately priced, but they have a limited life (usually not exceeding two years) and thus require periodic replacement.

As shown in Figures 1 to 4, the location of the peak emission concentration level in a road tunnel is a function of both traffic operation (unidirectional versus bidirectional) and type of ventilation provided (natural, longitudinal, semitransverse, or full transverse). Generally, time-averaged CO concentrations for the full length of the tunnel are needed to determine appropriate ventilation rates and/or required regulatory reporting. Time-averaged concentrations are particularly important in road tunnels where the ventilation system control is integrated with the CO monitoring system.

CO sampling locations in a road tunnel should be selected carefully to ensure meaningful results. For example, samples taken too close to an entry or exit portal do not accurately represent the overall level that can be expected throughout the tunnel. Multiple sampling locations are recommended to ensure that a reasonable average is reported. Multiple analyzers are also recommended to provide a reasonable level of redundancy in case of analyzer failure or loss of calibration. In longer road tunnels, which may have multiple, independently operated ventilation zones, the selected sampling locations should provide a representative CO concentration level for each ventilation zone. Strip chart recorders and microprocessors are commonly used to keep a permanent record of road tunnel CO levels.

CO analyzers and their probes should not be located directly in a roadway tunnel or in its exhaust plenum. Instead, an air pump should draw samples from the tunnel/exhaust duct through a sample line to the CO analyzer. This configuration eliminates the possibility of in-tunnel air velocities adversely affecting the instrument's accuracy. The length of piping between sampling point and CO analyzer should be as short as possible to maintain a reasonable air sample transport time.

Haze or smoke detectors have been used on a limited scale, but most of these instruments are optical devices and require frequent or constant cleaning with a compressed air jet. If traffic is predominantly diesel-powered, smoke haze and NO_x gases require individual monitoring in addition to that provided for CO.

Local regulations should be reviewed to determine whether ventilation exhaust monitoring is required for a particular road tunnel. If so, for tunnels using full transverse ventilation systems, CO and NO_2 pollutant sampling points should be placed carefully within the exhaust stacks/plenums. For longitudinally ventilated tunnels, sampling points should be located at least 100 ft in from the exit portal.
Controls.
Centralized Control. To expedite emergency response and to reduce the number of operating personnel for a given tunnel, all ventilating equipment should be controlled at a central location. New tunnels are typically provided with computer-based control systems, which function from operational control centers. In some older tunnel facilities, fan operation is manually controlled by an operator at a central control board. The control structure for newer road tunnel ventilation systems is typically supervisory control and data acquisition (SCADA), with programmable logic controllers (PLCs) providing direct control hardware over the associated electrical equipment. The operational control center varies from one stand-alone PC (with SCADA software providing dedicated ventilation control), to redundant client/server configurations providing an integrated control system and real-time database and alarm systems for tunnel operations (Buraczynski 1997). Communication links are required between the supervisory SCADA and PLCs.

The SCADA system operator controls the ventilation equipment through a graphical user interface, developed as part of the ventilation system design. Preprogrammed responses allow the operator to select the appropriate ventilation plan or incident response mode.

The SCADA system allows the operator to view equipment status, trend data values, log data, and use an alarm system. Whereas older tunnel facilities used chart recorders for each sampling point to demonstrate that the tunnel was sufficiently ventilated and compliant with environmental air quality standards, new tunnels use SCADA to log CO levels directly onto a nonvolatile medium, such as a CD-ROM.

Emergency response functions for road tunnel ventilation require that control system design meets life safety system standards. A high-availability system is required to respond on demand to fire incidents. High availability is obtained by using high-quality industrial components, and by adding built-in redundancy. The design must protect the system against common event failures; therefore, redundant communication links are segregated, and physically routed in separate raceways. High-integrity software for both the PLCs and the SCADA system is another major consideration.

Once a supervisory command is received, the PLC control handles equipment sequencing (e.g., fan and damper start-up sequence), least-hours-run algorithms, staggered starting of fans, and all interlocks. The PLC also receives instrumentation data from the fan and fan motor, and can directly shut down the fan if needed (e.g., because of high vibration). Conditions such as high vibration and high temperature are tolerated during emergency operation.

CO-Based Control. When input to the PLC, recorded tunnel air quality data allow fan control algorithms to be run automatically. The PLC controls fans during periods of rising and falling CO levels. Fan operations are usually based on the highest level recorded from several analyzers. Spurious high levels can occur at sampling points; the PLC control algorithm prevents the ventilation system from responding to short-lived high or low levels. PLC control also simplifies hardwired systems in older tunnel facilities, and increases flexibility through program changes.

Timed Control. This automatic fan control system is best suited for installations that experience heavy rush-hour traffic. With timed control, the fan operation schedule is programmed to increase the ventilation level, in preset increments, before the anticipated traffic increase; it can also be programmed for weekend and public holiday conditions. The timed control system is relatively simple and is easily revised to suit changing traffic patterns. Because it anticipates an increased airflow requirement, the associated ventilation system can be made to respond slowly, and thus avoid expensive demand charges from the local utility company. One variation of timed control is to schedule the minimum anticipated number of fans to run, and to start additional fans if high CO levels are experienced. As with the CO-based control system, a manual override is needed to cope with unanticipated conditions.

Traffic-Actuated Control. Several automatic fan control systems have been based on the recorded flow of traffic. Most require installation of computers and other electronic equipment needing specific maintenance expertise.

Local Fan Control. Local control panels are typically provided for back-up emergency ventilation control and for maintenance/servicing requirements. The local panels are often hardwired to the fan starters to make them independent from the normal SCADA/PLC control system. Protocols for handing over fan control from the SCADA/PLC system to the local panel must also be established, so that fans do not receive conflicting operational signals during an emergency.

Rapid Transit Tunnels and Stations

Modern high-performance, air-conditioned subway vehicles consume most of the energy required to operate rapid transit and are the greatest source of heat in the underground areas of a transit system. An environmental control system (ECS) is intended to maintain reasonable comfort during normal train operations, and help keep passengers safe during a fire emergency. Minimizing traction power consumption and vehicle combustible contents reduces ventilation requirements. The large amount of heat produced by rolling stock, if not properly controlled, can cause passenger discomfort, shorten equipment life, and increase maintenance requirements. Tropical climates present additional concerns for underground rail transit systems and make environment control more critical.

Temperature, humidity, air velocity, air pressure change, and rate of air pressure change help determine ECS performance. These conditions are affected by time of day (i.e., morning peak, evening peak, or off-peak), circumstance (i.e., normal, congested, or emergency operations), and location in the system (i.e., tunnel, station platform, entrance, or stairway). The *Subway Environmental Design Handbook* (SEDH) (DOT 1976) provides comprehensive and authoritative design aids on ECS performance; information in the SEDH is based on design experience, validated by field and model testing.

Normal operations involve trains moving through the subway system according to schedule, and passengers traveling smoothly through stations to and from transit vehicles. The piston action of moving trains is the chief means of providing ventilation and maintaining an acceptable environment (i.e., air velocity and temperature) in the tunnels. Because normal operations are predominant, considerable effort should be made to optimize ECS performance during this mode.

One concern is limiting the air velocity caused by approaching trains on passengers waiting on the platform. Piston-induced platform air velocities can be reduced by providing a pressure relief shaft (also known as a blast shaft) at each end of affected platforms.

During normal train operations, platform passenger comfort is a function of the temperature and humidity of ambient and station air, platform air velocity, and duration of exposure to the station environment. For example, a person entering an 84°F station from 90°F outdoor conditions will momentarily feel more comfortable, particularly after a fast-paced walk ending with total rest, even if standing. However, in a short time, usually about 6 min, the person's metabolism adjusts to the new environment and produces a similar level of comfort as before. If a train were to arrive during this period, a relatively high station air temperature would be acceptable. The relative warmth index (RWI) quantifies this transient effect, allowing the designer to select an appropriate design air temperature for the station based on the transient, rather than steady-state, sensation of comfort. Design temperatures based on the transient approach are typically higher (often 5 to 9°F) than those selected by the steady-state approach, and hence result in reduced cooling load and air-conditioning system requirements.

Congested operations result from delays or operational problems that prevent the normal dispatch of trains, such as missed headways or low-speed train operations. Trains may wait in stations, or stop at predetermined locations in tunnels during congested operations. Delays usually range from 30 s to 20 min, although longer delays may occasionally be experienced. Passenger evacuations or endangerment are not expected to occur. Congested ventilation analyses should focus on the potential need for forced (mechanical) ventilation, which may be required to control tunnel air temperatures in support of continued operation of train air-conditioning units. The aim of forced ventilation is to maintain onboard passenger comfort during congestion by operating the vehicle air conditioning system to prevent passengers from evacuating the train.

Emergency operations occur as a result of a fire in a subway tunnel or station. Fire emergencies include trash fires, track electrical fires, train electrical fires, and acts of arson. Some fires may involve entire train cars. Station fires are mostly trashcan fires. Statistically, most fire incidents reported in mass transit systems (up to 99%) are small, and low in smoke generation; these fires typically cause only minor injuries and operational disturbances. The most serious emergency condition is a fire on a stopped train in a tunnel; this event disrupts traffic and requires passenger evacuation. For this case, adequate tunnel ventilation is required to control smoke flow and enable safe passenger evacuation and safe ingress of emergency response personnel. Though rare, tunnel fires must be considered because of their potential life-safety ramifications.

Design Concepts. Elements of underground rail transit ventilation design may be divided into four interrelated categories: natural, mechanical, and emergency ventilation; and station air conditioning.

Natural Ventilation. Natural ventilation (e.g., ambient air infiltration and exfiltration) in subway systems primarily results from trains moving in tightly fitting tunnels, where air generally moves in the direction of train travel. The positive air pressure generated in front of a moving train expels warm air from the subway through tunnel portals, pressure relief shafts, station entrances and other openings; the negative pressure in the wake induces airflow into the subway through these same openings.

Considerable short-circuiting of airflow occurs in subways when two trains, traveling in opposite directions, pass each other; especially in stations or tunnels with porous walls (those with intermittent openings to allow air passage between trackways). Short-circuiting can also occur in stations and tunnels with nonporous walls where alternative airflow paths (e.g., open bypasses, cross-passageways, adits, crossovers) exist between the trackways. This short-circuited airflow reduces the net ventilation rate and increases air velocities on platforms and in entrances. During peak operating periods and high ambient temperatures, short-circuited airflow can cause undesirable heat build-up in the station.

To counter the negative effects of short-circuiting airflow, ventilation shafts are customarily located near interfaces between tunnels and stations. Shafts in station approach tunnels are often called blast shafts, because part of the tunnel air pushed by an approaching train is expelled through them before it affects the station environment. Shafts in station departure tunnels are known as relief shafts, because they relieve the negative air pressure created by departing trains. Relief shafts also induce outside airflow through the shaft, rather than through station entrances.

Additional shafts may be provided for natural ventilation between stations (or between portals, for underwater crossings), as dictated by tunnel length. The high cost of such ventilation structures necessitates a design that optimizes effectiveness and efficiency. Internal resistance from offsets and bends in the ventilation shaft should be kept to a minimum; shaft cross-sectional area should approximately equal the cross-sectional area of a single-track tunnel (DOT 1976).

Mechanical Ventilation. Mechanical ventilation in subways (1) supplements the natural ventilation effects of moving trains, (2) expels warm air from the system, (3) introduces fresh outside air, (4) supplies makeup air for exhaust, (5) restores the cooling potential of the tunnel heat sink by extracting heat stored during off hours or system shutdown, (6) reduces airflow between the tunnel and station, (7) provides outside air for passengers in stations or tunnels during an emergency or other unscheduled interruptions of traffic, and (8) purges smoke from the system during a fire, protecting the passengers' evacuation.

The most cost-effective design for a mechanical ventilation system serves multiple purposes. For example, a vent shaft designed for natural ventilation may also be used for emergency ventilation if a fan is installed in parallel, as part of a bypass (Figure 8). Current safety standards require emergency fans to be reversible (NFPA *Standard* 130).

Several ventilation shafts and fan plants may be required to work together to achieve many, if not all, of the eight design objectives. Depending on the shaft location, design, and local train operating characteristics, a shaft with an open bypass damper and a closed fan
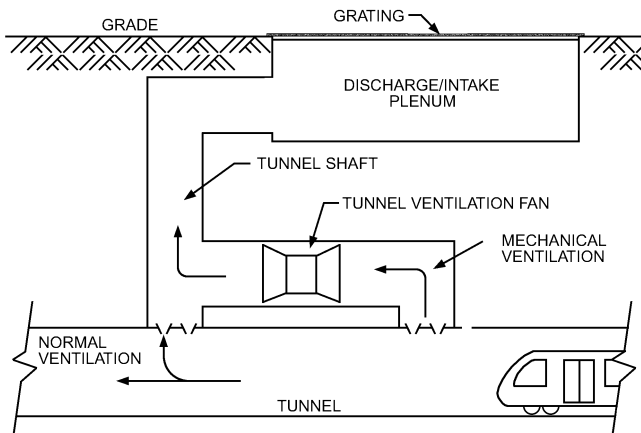
damper may serve as a blast or relief shaft. With the fan damper open and the bypass damper closed, air can be supplied to or exhausted from the tunnel, depending on fan rotation direction. Except for emergency ventilation, fan rotation direction is usually predetermined for various operating modes.

If a station is not air conditioned, warm air in the subway should be exchanged, at the maximum rate possible, with cooler outside air. If a station is air conditioned below the ambient temperature, inflow of warmer outside air should be limited and controlled.

Figure 9 shows a typical tunnel ventilation system between two subway stations. Here the flow of warm tunnel air into the station is minimized by either normal or mechanical ventilation effects. In Figure 9A, the air pushed ahead of the train on track 2 diverts partially to the bypass ventilation shaft and partially into the wake of a train on track 1, as a result of pressure differences. Figure 9B shows an alternative operation with the same ventilation system where midtunnel fans operate in exhaust mode; when outdoor air conditions are favorable, makeup air is introduced through the bypass ventilation shafts. This alternative can also either provide or supplement station ventilation. To achieve this, the bypass shafts are closed, and makeup air for the mid-tunnel exhaust fans enters through station entrances.

A more direct mechanical ventilation system (Figure 10) can be designed to remove station heat at its primary source, the underside of the train. Field tests have shown that trackway ventilation systems not only reduce upwelling of warm air into the platform areas, but also remove significant portions of heat generated by other undercar sources, such as dynamic-braking resistor grids and, in some cases, air-conditioning condenser units (DOT 1976). Ideally, makeup air for trackway exhaust should be introduced at track level, as in Figure 10A, to provide positive control over the direction of airflow; however, obstructions in the vehicle undercarriage area must be avoided when planning underplatform exhaust port and makeup air supply locations.

A trackway ventilation system without a dedicated makeup air supply (Figure 10B), also known as an underplatform exhaust (UPE) system, is the least effective alternative for heat removal. With a UPE system, a quantity of air equal to that withdrawn by the underplatform exhaust enters the station control volume, either from outside or from the tunnels. When the ambient, or tunnel, air temperature is higher than the station design air temperature, a UPE system reduces station heat load by removing undercar heat, but it also increases station heat load by drawing in warmer air, which may affect platform passenger comfort.

Fig. 8   Tunnel Ventilation Shaft

Fig. 9   Tunnel Ventilation Concept

A. OUTSIDE AIR MAKEUP AT TRACK LEVEL

B. NO MAKEUP AIR SUPPLY

C. MAKEUP AIR SUPPLY AT CEILING LEVEL
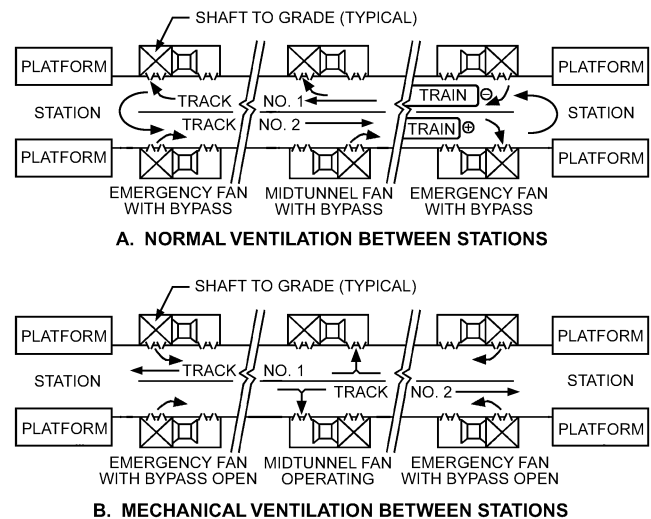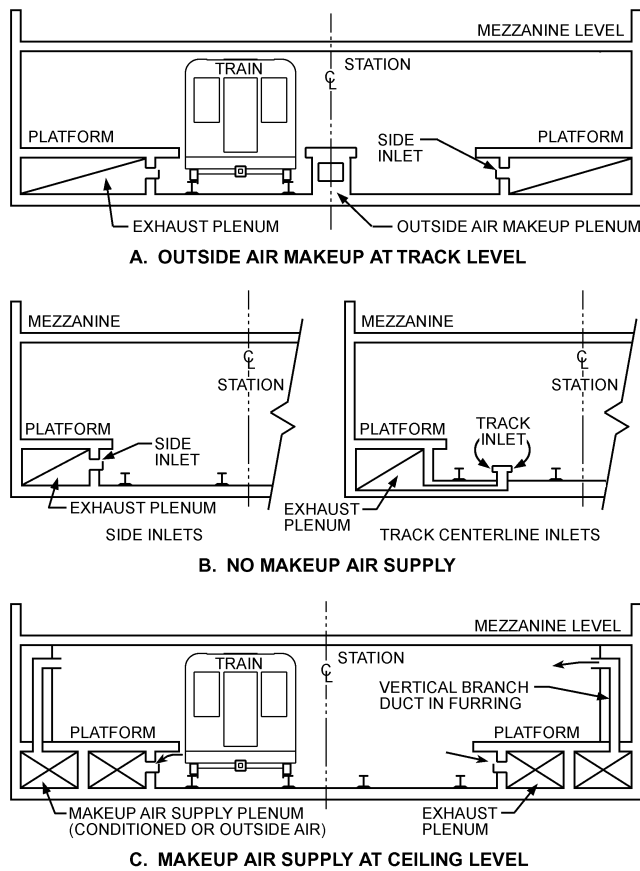
Fig. 10   **Trackway Ventilation Concept (Cross-Sections)**

Fig. 11   **Emergency Ventilation Concept**

Figure 10C shows a cost-effective compromise: makeup air is introduced from the ceiling above the platform. Although heat removal effectiveness of this system may be less than that of the system with track-level makeup air, the inflow of warm tunnel air that may occur in a system without makeup air supply is negated.

Newer vehicles have air-conditioning grids above, generating heat near the ceiling during dwell time in the station. To exhaust this heat, an overtrack exhaust (OTE) system should be provided.

Emergency Ventilation. During a subway tunnel fire, mechanical ventilation is a major part of the response and smoke control strategy. Fires induce the airflow required to support combustion and growth. Activating an emergency fan system increases the air supply over that required for combustion and tends to reduce the progression of the fire by lowering the flame temperature, but it also generates additional smoke because the percentage of incomplete combustion is increased. More importantly, an emergency ventilation system should be implemented in a subway system to control the direction of smoke migration and permit safe evacuation of passengers and access by firefighters (see NFPA *Standard* 130).

The most common method of ventilating a tunnel during a fire is push-pull fan operation: fans on one side of the fire operate in supply mode, while fans on the opposite side operate in exhaust mode. Emergency ventilation analyses should focus on determining the airflow required to preserve tenable conditions in a single evacuation path from the train. The criterion used to design emergency ventilation for underground transit systems is critical velocity, similar to that presented in the section on Road Tunnels. The presence of nonincident trains should be considered in planning the emergency ventilation system response to specific fire incidents.

Emergency ventilation system design must allow for the unpredictable location of both the disabled train and the fire source.
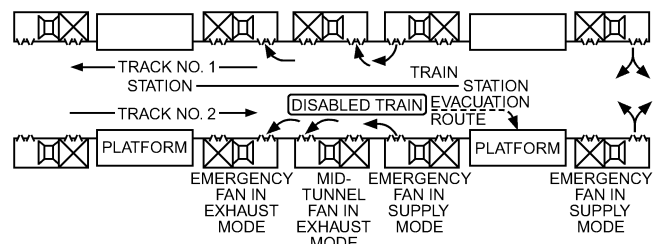
Therefore, emergency ventilation fans should have full reverse-flow capability, so that fans on either side of a disabled train can operate together to control airflow direction and counteract undesired smoke migration.

When a disabled train is stopped between two stations and fire or smoke is discovered, outside air is supplied by the emergency ventilation fans at the nearest station, and smoke-laden air is exhausted past the opposite end of the train by emergency ventilation fans at the next station, unless the location of the fire dictates otherwise. Passengers can then be evacuated along the tunnel walkways via the shortest possible route (Figure 11).

Emergency ventilation analysis should consider the possibility of nonincident trains stopped behind the disabled train. In this case, emergency fans should be operated so that nonincident trains are kept in the fresh airstream; if possible, they may be used to evacuate incident-train passengers. For long subway tunnels, in particular, analysis should also consider evacuating passengers to a nonincident trackway (through cross passageways), where a dedicated rescue train can move them to safety. Emergency ventilation analyses should identify passenger evacuation/firefighter ingress routes for evaluated scenarios, and fan modes to preserve tenable conditions in those routes.

When a train fire is discovered, the train should be moved if possible to the next station, to make passenger evacuation and fire suppression easier. Emergency management plans must include provisions to (1) quickly assess any fire or smoke event, (2) communicate the situation to an operations control center, (3) establish the location of the incident train, (4) establish the general location of the fire, (5) determine the best passenger evacuation route, and (6) quickly activate emergency ventilation fans to establish smoke flow control.

Midtunnel and station trackway ventilation fans may be used to enhance emergency ventilation; therefore, these fans must also operate under high temperatures and have reverse-flow capability.

The possibility of a fire on the station platform or in another public area should also be considered. These fires are generally created by rubbish or wastepaper, and are thus much smaller than train fires. However, small station fires can generate considerable smoke and create panic among passengers. Therefore, stations should be equipped with efficient fire suppression and smoke extraction systems. Stations with platform-edge doors should have fire suppression and smoke extraction systems designed specifically for that configuration.

The fire heat release rate is an important parameter in subway emergency ventilation system design. Typical fire size data for single transit vehicles are as follows:

- Older transit vehicle $\approx 50 \times 10^6$ Btu/h
- New, hardened vehicle $\approx 35 \times 10^6$ Btu/h
- Light rail vehicle $\approx 30 \times 10^6$ Btu/h

Smoke obscuration is a key factor in defining a tenable environment for passenger evacuation, and visibility is often the governing criterion for station design. The smoke release rate should be calculated following acceptable procedures [e.g., Society of Fire Protection Engineers (SFPE) 2002].

Station Air Conditioning. Faster station approach speeds and closer headways, both made possible by computerized train control, have increased heat gains in subway stations. The net internal sensible heat gain for a typical two-track subway station, with 40 trains per hour per track traveling at a top speed of 50 mph, may reach 5.0×10^6 Btu/h, even after some tunnel heat is removed by the heat sink, station underplatform exhaust system, or tunnel ventilation system. To remove this heat from a station with a ventilation system using outside air and a maximum air temperature increase of 3°F, for example, would require roughly 1.4×10^6 cfm of outside air. This would be costly, and air velocities on the platforms would be objectionable to passengers.

The same amount of sensible heat gain, plus the latent heat and outside air loads (based on a station design air temperature 7°F lower than ambient), could be handled by about 630 tons of refrigeration. Even if station air conditioning is more expensive at the outset, long-term benefits include (1) reduced design airflow rates, (2) reduced ventilation shaft/duct sizing, (3) improved passenger comfort, (4) increased service life of other station equipment (e.g., escalators, elevators, fare collection), (5) reduced maintenance requirements for station equipment and structures, and (6) increased acceptance of the subway as a viable means of public transportation. Air conditioning should also be considered for other station ancillary areas, such as concourse levels and transfer levels. However, unless these walk-through areas are designed to attract patronage to concessions, the cost of air conditioning is usually not warranted.

The physical configuration of the station platform level usually determines the cooling distribution pattern. Platform areas with high ceilings, local warm spots created by trains, high-density passenger accumulation, or high-level lighting may need spot cooling. Conversely, where the train length equals platform length and the ceiling height above the platform is limited to 10 to 11.5 ft, isolating heat sources and using spot cooling are usually not feasible.

Air conditioning is more attractive and efficient for stations with platform-edge doors, which limit air exchange between platform and tunnels. In tropical climates, separate ventilation systems are typically used to minimize station air exfiltration and tunnel air infiltration through platform-edge doors.

Space use in a station structure for air-distribution systems is of prime concern because of the high cost of underground construction. Overhead distribution ductwork could add to the depth of excavation during subway construction. The space beneath a subway station platform is normally an excellent area for low-cost distribution of supply, return, and/or exhaust air.

Design Method. Subways typically have two discrete sets of environmental criteria: one for normal train operations and one for emergency fire/ smoke operations. Criteria for normal operations include limits on tunnel air temperature and humidity for various times of the year, minimum ventilation rates to dilute contaminants generated in the subway, and limits on the air velocity and rate of air pressure change to which passengers may be exposed. Some of these criteria are subjective and may vary based on demographics. Criteria for emergency operations include a minimum purge time to remove smoke from a subway, critical air velocity for smoke flow control during a tunnel fire, and minimum and maximum fan-induced tunnel air velocities.

Given a set of criteria, outdoor design conditions, and appropriate tools for estimating interior heat loads, heat sink effect, ventilation requirements, tunnel air velocity, and rate of air pressure changes, design engineers can select components for the environmental control system (ECS). ECS design should consider controls for tunnel air temperature, velocity, and quality, and the air pressure change rate. Systems selected generally combine natural and mechanical ventilation, underplatform exhaust, and station air conditioning.

Train propulsion/braking systems and the configuration of the tunnels and stations greatly affect the subway environment. Therefore, the ECS must often be considered during the early stages of subway system design. Factors affecting a subway environmental control system are discussed in this section. The *Subway Environmental Design Handbook* (SEDH) (DOT 1976) and NFPA *Standard* 130 have additional information.

Analytical Data. ECS design should be based on all the parameters affecting its operation, including ambient air conditions, train operating characteristics, applicable ventilation methods, new or existing ventilation structures, and calculated heat loads. ECS efficiency should be addressed early during transit system design. The tunnel ventilation system should be integrated with the design of other tunnel systems (including power, signaling, communications, and fire/life safety systems) and with the station ventilation system design. The ECS design must satisfy the project design criteria and comply with applicable local and national (or international) codes, standards, and regulations.

The ventilation engineer should be familiar with these requirements and apply suitable design techniques, such as computer modeling and simulations (using verified/validated engineering software).

Comfort Criteria. Because passenger exposure to the subway environment is transient, comfort criteria are not as strict as those for continuous occupancy. As a general principle, the station environment should provide a smooth transition between outside air conditions and thermal conditions in the transit vehicles. For passenger comfort, the preferred air velocity is between 500 and 1000 fpm in public areas during normal train operations.

Air Quality. Air quality in a subway system is influenced by many factors, some of which are not under the direct control of the HVAC engineer. Some particulates, gaseous contaminants, and odorants in the ambient air can be prevented from entering the subway system by judicious selection of ventilation shaft locations. Particulate matter, including iron and graphite dust generated by normal train operations, is best controlled by regularly cleaning stations and tunnels. However, the only viable way to control gaseous contaminants in a subway system, such as ozone (produced by electrical equipment) and CO_2 (from human respiration), is through adequate ventilation with outside air.

Subway system air quality should be analyzed either by engineering calculations or by computer modeling and simulations. The analysis should consider both the tunnel airflow induced by the piston effect of moving trains and the outside airflow required to dilute gaseous contaminants to acceptable levels. The results should comply with the *Subway Environmental Design Handbook* (DOT 1976) recommendation for at least 4 ach, as well as the recommendation of ANSI/ASHRAE *Standard* 62.1 to have a minimum of 15 cfm outside air per person. Maximum station occupancy should be used in the analysis.

Pressure Transients. Trains passing through aerodynamic discontinuities in a subway cause changes in tunnel static pressure, which can irritate passengers' ears and sinuses. Based on nuisance factor criteria, if the total change in the air pressure is greater than 2.8 in. of water, the rate of static pressure change should be kept below 1.7 in. of water per second. Pressure transients also add to the dynamic load on various equipment (e.g., fans, dampers) and appurtenances (e.g., acoustical panels). The formula and methodology of pressure transient calculations are complex; this information is presented in the SEDH (DOT 1976).

Air Velocity. During fires, emergency ventilation must be provided in the tunnels to control smoke flow and reduce air temperatures to permit both passenger evacuations and firefighting operations. The minimum air velocity in the affected tunnel should be sufficient to prevent smoke from backlayering (flowing in the upper cross section of the tunnel in the direction opposite the forced ventilation airflow). The method for ascertaining this minimum air velocity is provided in DOT (1976). The maximum tunnel air velocity experienced by evacuating passengers should not exceed 2200 fpm.

Interior Heat Loads. Heat in a subway is generated mostly by the following sources:

- Train deceleration/braking: Between 40 and 50% of heat generated in a subway arises from train deceleration/braking. Many vehicles use nonregenerative braking systems, in which the kinetic energy of the train is dissipated to the tunnel as heat, through dynamic and/or frictional brakes, rolling resistance, and aerodynamic drag. Regenerative systems dissipate less braking heat.
- Train acceleration: Heat is also generated as a train accelerates. Many vehicles use cam-controlled variable-resistance elements to regulate voltage across dc traction motors during acceleration. Electrical power is dissipated by these resistors (and the third rail) as heat into the subway. The heat released during train acceleration also comes from traction motor losses, rolling resistance, and aerodynamic drag. Heat from acceleration generally amounts to 10 to 20% of the total heat released in a subway system.

In subway systems with closely spaced stations, more heat is generated because of the frequent acceleration and deceleration.

- Vehicle air conditioning: Most new transit vehicles are fully climate-controlled. Air-conditioning equipment removes passenger and lighting heat from the cars and transfers it, along with condenser fan and compressor heat, into the subway. Vehicle air-conditioning system capacities generally range from 10 tons per vehicle for shorter rail cars (about 50 ft long), up to about 20 tons for longer rail cars (about 70 ft long). Heat from vehicle air conditioning and other accessories is generally 25 to 30% of total heat generated in a subway.
- Other sources: Tunnel heat also comes from people, lighting, induced outside air, miscellaneous equipment (e.g., fare collecting machines, escalators), and third-rail/catenary systems. These sources can generate 10 to 30% of the total heat released in a subway.

In a typical subway heat balance analysis, a control volume is defined around each station and heat sources are identified and quantified. The control volume usually includes the station and its various approach/departure tunnels. Typical values for heat emission/rejection data are given in Table 6.

Heat Sink. The amount of heat flow from tunnel air to subway walls varies seasonally, as well as during morning and evening rush-hour operations. Short periods of abnormally high or low outside temperature may cause a temporary departure from the normal heat sink effect in unconditioned areas of the subway, changing the average tunnel air temperature. However, any change from the normal condition is diminished by the thermal inertia of the subway structure. During abnormally hot periods, heat flow from the tunnel air to subway walls increases. Similarly, during abnormally cold periods, heat flow from the subway walls to tunnel air increases.

For subway systems where daily station air temperatures are held constant by dedicated heating and cooling systems, heat flux from station walls is negligible. Depending on the amount of station air flowing into adjoining tunnels, heat flux from tunnel sections may also be reduced. Other factors affecting the heat sink component are

Table 6   Typical Heat Source Emission Values

Source of Heat	Heat Rejection, Btu/h
Train A/C system (per vehicle)	144,000
Escalator (10 hp, 75% load factor)	19,100[a]
Fare collection machine	2730[a]
Station lighting	10.2 per square foot[a]
People (walking, standing)	250 sensible[b]
	250 latent[b]

[a]See *Subway Environmental Design Handbook*, Part 3 (DOT 1976).
[b]See 2005 *ASHRAE Handbook—Fundamentals*, Chapter 30.

soil type (dense rock or light, dry soil), extent of migrating groundwater or the local water table, and surface configuration of tunnel walls (ribbed or flat).

Measures to Limit Heat Loads. Various measures have been proposed to limit interior heat loads in subway systems, including regenerative braking, thyristor motor controls, track profile optimization, underplatform exhaust systems, and cooling dumping.

Electrical regenerative braking converts kinetic energy into electrical energy for use by other trains. Flywheel energy storage, an alternative form of regenerative braking, stores part of the braking energy in high-speed flywheels for use during vehicle acceleration. These methods can reduce the heat generated in train braking by approximately 25%.

Cam-controlled propulsion applies a set of resistance elements to regulate traction motor current during acceleration. Electrical energy dissipated by these resistors appears as waste heat in a subway. **Thyristor motor controls** replace the acceleration resistors with solid-state controls, which reduce acceleration-related heat losses by about 10% on high-speed subways, and by about 25% on low-speed subways.

Track profile optimization refers to a tunnel design that is lower between the stations. Less power is used for acceleration, because some of the potential energy of a standing train is converted to kinetic energy as the train accelerates toward the tunnel low point. Conversely, some of the kinetic energy of a train at maximum speed is converted to potential energy during braking, as the train approaches the next station. Track profile optimization reduces the maximum vehicle heat loss from acceleration and braking by about 10%.

An **underplatform exhaust (UPE)** system, described in the section on Mechanical Ventilation, uses a hood to remove heat generated by vehicle underfloor equipment (e.g., resistors, air-conditioning condensers) from the station environment. SEDH (DOT 1976) provides a table (based on field test results) of various UPE airflow rates versus UPE system efficiency. For preliminary calculations, it may be assumed that (1) the train heat release (from braking and air conditioning) in the station box is about two-thirds of the control-volume heat load, and (2) the UPE is about 50% effective.

In tropical areas, where there are only small daily differences in the ambient air temperature, tunnel walls do not cool off during the night; consequently the heat sink effect is negligible. In such cases, **cooling dumping** (releasing cooler air from the vehicle or its air-conditioning system) can be considered to limit heat accumulation in subway tunnels. However, the effect of cooling dumping on vehicle air-conditioning systems must be considered.

Railroad Tunnels

Railroad tunnels for diesel locomotives require ventilation to remove residual diesel exhaust, so that each succeeding train is exposed to a relatively clean air environment. Ventilation is also required to prevent locomotives from overheating while in the tunnel. For short tunnels, ventilation generated by the piston effect of a train, followed by natural ventilation, is usually sufficient to purge the tunnel of diesel exhaust in a reasonable time period. Mechanical ventilation for locomotive cooling is usually not required in short tunnels, because the time that a train is in the tunnel is typically less than the time it would take for a locomotive to overheat. However, under certain conditions, such as for excessively slow trains or during hot weather, locomotive overheating can still become a problem. For long tunnels, mechanical ventilation is required to purge the tunnel of diesel exhaust, and may also be required for locomotive cooling, depending on the speed of the train and the number and arrangement of locomotives used.

The diesel locomotive is essentially a fuel-driven, electrically powered vehicle. The diesel engine drives a generator, which in turn supplies electrical power to the traction motors. The power of these engines ranges from about 1000 to 6000 hp. Because the overall

Fig. 12   Typical Diesel Locomotive Arrangement

efficiency of the locomotive is generally under 30%, most of the energy generated by the combustion process must be dissipated as heat to the surrounding environment. Most of this heat is released above the locomotive through the engine exhaust stack and the radiator discharge (Figure 12).

In a tunnel, this heat is confined to the region surrounding the train. Most commercial trains are powered by more than one locomotive, so the last unit is subjected to heat released by preceding units. If sufficient ventilation is not provided, the air temperature entering the radiator of the last locomotive will exceed its allowable limit. Depending on the engine protection system, this locomotive will then either shut down or drop to a lower throttle position. In either event, the train will slow down. But, as discussed in the next section, a train relies on its speed to generate sufficient ventilation for cooling. As a result of the train slowing down, a domino effect takes place, which may cause the train to stall in the tunnel.

Design Concepts. Most long railroad tunnels (over 5 mi) in the western hemisphere that serve diesel operation use a ventilation concept using both a tunnel door and a system of fans and dampers, all located at one end of the tunnel. When a train moves through the tunnel, ventilation air for locomotive cooling is generated by the piston effect of the train moving toward (or away from) the closed portal door. This effect often creates a sufficient flow of air past the train for self-cooling.

Under certain conditions, when the piston effect cannot provide required airflow, fans supplement the flow and cool the tunnel. When the train exits at the portal, the tunnel is purged of residual smoke and diesel contaminants by running the fans (with the door closed) to move fresh air from one end of the tunnel to the other. Because the airflow and pressure required for cooling and purge modes may be substantially different, multiple fan systems or variable-volume fans may be required for the two operations. Also, dampers are provided to relieve the pressure across the door, which facilitates its operation while the train is in the tunnel.

Application of this basic ventilation concept varies depending on the length and grade of the tunnel, type and speed of the train, environmental and structural site constraints, and train traffic flow. One

design, for a 9 mi long tunnel (Levy and Danziger 1985), extended the basic concept by including a mid-tunnel door and a partitioned shaft, which was connected to the tunnel on both sides of the mid-tunnel door. The combination of mid-tunnel door and partitioned shaft divided the tunnel into two segments, each with its own ventilation system. Thus, the ventilation requirement of each segment was satisfied independently. The need for such a system was dictated by the length of the tunnel, relatively low speed of the trains, and traffic pattern.

Locomotive Cooling Requirements. A breakdown of the heat emitted by a locomotive to the surrounding air can be determined by performing an energy balance. Starting with the fuel consumption rate (as a function of the throttle position), the heat release rates (as provided by the engine manufacturer) at the engine exhaust stack and radiator discharge, and the gross power delivered by the engine shaft (as determined from manufacturer's data), the amount of miscellaneous heat radiated by a locomotive can be determined as follows:

$$q_M = FH - q_S - q_R - P_G \qquad (9)$$

where

q_M = miscellaneous heat radiated from locomotive engine, Btu/h
F = locomotive fuel consumption, lb/h
H = heating value of fuel, Btu/lb
q_S = heat rejected at engine exhaust stack, Btu/h
q_R = heat rejected at radiator discharge, Btu/h
P_G = gross power at engine shaft, Btu/h

Because locomotive auxiliaries are driven off the engine shaft, with the remaining power used for traction power through the main engine generator, heat released by the main engine generator can be determined as follows:

$$q_G = (P_G - L_A)(1 - \varepsilon_G) \qquad (10)$$

where

q_G = main generator heat loss, Btu/h
L_A = power driving locomotive auxiliaries, Btu/h
ε_G = main generator efficiency

Heat loss from the traction motors and gear trains can be determined as follows:

$$q_{TM} = P_G - L_A - q_G - P_{TE} \qquad (11)$$

where

q_{TM} = heat loss from traction motors and gear trains, Btu/h
P_{TE} = locomotive tractive effort power, Btu/h

The total locomotive heat release rate q_T can then be determined:

$$q_T = q_S + q_R + q_m + L_A + q_G + q_{TM} \qquad (12)$$

For a train with N locomotives, the average air temperature approaching the last locomotive is determined from

$$t_{AN} = t_{AT} + \frac{q_T(N-1)}{\rho c_p Q_R} \qquad (13)$$

where

t_{AN} = average tunnel air temperature approaching Nth locomotive, °F
t_{AT} = average tunnel air temperature approaching locomotive consist, °F
ρ = density of tunnel air approaching locomotive consist, lb/ft³
c_p = specific heat of air, Btu/lb$_m$·°F
Q_R = tunnel airflow rate relative to train, ft³/h

The inlet air temperature to the locomotive radiators is used to judge the adequacy of the ventilation system. For most locomotives running at maximum throttle position, the maximum inlet air

temperature recommended by manufacturers is about 115°F. Field tests in operating tunnels (Aisiks and Danziger 1969; Levy and Elpidorou 1991) showed, however, that some units can operate continuously with radiator inlet air temperatures as high as 135°F. The allowable inlet air temperature for each locomotive type should be obtained from the manufacturer when contemplating a design.

To determine the airflow rate required to prevent a locomotive from overheating, the relationship between the average tunnel air temperature approaching the last unit and the radiator inlet air temperature must be known, or conservatively estimated. This relationship depends on variables such as the number of locomotives in the consist, air velocity relative to the train, tunnel cross-sectional area/configuration, type of tunnel lining, and locomotive orientation (i.e., facing forward or backward). For trains traveling under 20 mph, Levy and Elpidorou (1991) showed that a reasonable estimate is to assume the radiator inlet air temperature to be about 10°F higher than the average air temperature approaching the unit. For trains moving at 30 mph or more, a reasonable estimate is to assume that the radiator inlet air temperature equals the average air temperature approaching the unit. When the last unit of the train consist faces forward, thereby putting the exhaust stack ahead of its own radiators, the stack heat release rate must be included when evaluating the radiator inlet air temperature.

Tunnel Aerodynamics. When designing a ventilation system for a railroad tunnel, airflow and pressure distribution throughout the tunnel (as a function of train type, train speed, and ventilation system operating mode) must be determined. This information is required to determine (1) whether sufficient ventilation is provided for locomotive cooling, (2) the pressure that the fans are required to deliver, and (3) the pressure that the structural and ventilation elements of the tunnel must be designed to withstand.

The following equation, from DOT (1997a), relates the piston effect of the train, steady-state airflow from fans to the tunnel, and pressure across the tunnel door. This expression assumes that air leakage across the tunnel door is negligible. Figure 13 shows the dimensional variables on a schematic of a typical tunnel.

$$\frac{\Delta p}{\rho}\left(\frac{g_C}{g}\right) = \frac{(p_A - p_B)}{\rho}\times\left(\frac{g_C}{g}\right) - H$$

$$+ \left[\frac{(A_V^2 + A_V A_T C_{DVB})}{(A_T - A_V)^2} + \frac{A_V C_{DVF}}{A_T}\right]\frac{(A_T V + Q_S)^2}{2A_T^2 g}$$

$$+ \frac{f_T L_V P_T (A_V V + Q_S)^2}{8(A_T - A_V)^3 g} + \frac{\lambda_V L_V P_V (A_T V + Q_S)^2}{8(A_T - A_V)^3 g}$$

$$+ \frac{f_T (L_T - L_V) P_T Q_S^2}{8A_T^3 g} + \frac{K Q_S^2}{2A_T^2 g} \tag{14}$$

where

Δp = static pressure across tunnel door, lb_f/ft^2
ρ = density of air, lb_m/ft^3
p_A = barometric pressure at portal A, lb_f/ft^2
p_B = barometric pressure at portal B, lb_f/ft^2
H = difference in elevation between portals, ft
g = acceleration of gravity = 32.2 ft/s^2
g_C = gravitational constant = 32.2 $ft \cdot lb_m/lb_f \cdot s^2$
A_V = train cross-sectional area, ft^2
A_T = tunnel cross-sectional area, ft^2
C_{DVB} = drag coefficient at back end of train
C_{DVF} = drag coefficient at front end of train
V = velocity of train, ft/s
Q_S = airflow delivered by fan, ft^3/s
f_T = tunnel wall friction factor
L_T = tunnel length, ft
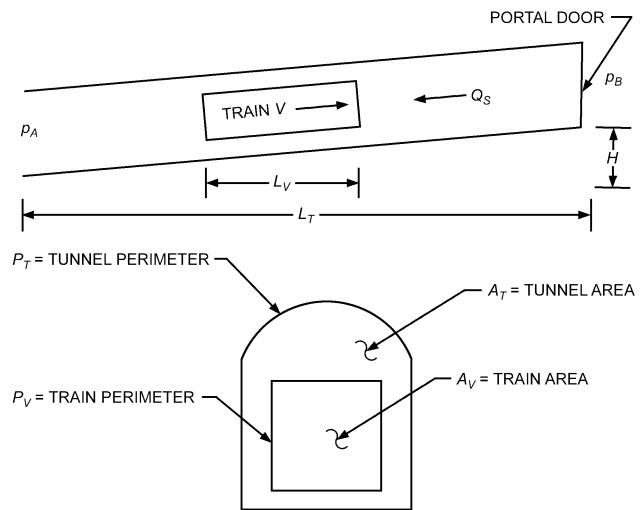
Fig. 13 Railroad Tunnel Aerodynamic Related Variables

L_V = train length, ft
P_T = tunnel perimeter, ft
P_V = train perimeter, ft
λ_V = train skin friction factor
K = miscellaneous tunnel loss coefficient

The pressure across the tunnel door generated only by train piston action is evaluated by setting Q_S equal to zero. The airflow rate, relative to the train, required to evaluate locomotive cooling requirements is

$$Q_{rel} = A_T V + Q_S \tag{15}$$

where Q_{rel} is the airflow rate relative to the train, ft^3/s.

Typical values for C_{DVB} and C_{DVF} are about 0.5 and 0.8, respectively. Because trains passing through a railroad tunnel are often more than 1 mi long, the parameter that most affects the generated air pressure is the train skin friction coefficient. For dedicated coal or grain trains, which essentially use uniform cars throughout, a value of 0.09 for the skin friction coefficient results in air pressure predictions that conform closely to those observed in various railroad tunnels. For trains with nonuniform car distribution, the skin friction coefficient may be as high as 1.5 times that for a uniform car distribution.

The wall surface friction factor corresponds to the coefficient used in the Darcy-Weisbach equation for friction losses in pipe flow. Typical effective values for tunnels constructed with a formed concrete lining and having a ballasted track range from 0.015 to 0.017.

Tunnel Purge. The leading end of a locomotive must be exposed to an environment that is relatively free of smoke and diesel contaminants emitted by preceding trains. Railroad tunnels are usually purged by displacing contaminated tunnel air with fresh air by mechanical means after a train has left the tunnel. With the tunnel door closed, air is either supplied to or exhausted from the tunnel, moving fresh air from one end of the tunnel to the other. Observations at the downstream end of tunnels have found that an effective purge time is usually based on displacing 1.25 times the tunnel volume with outside air.

The time required for purging is primarily determined by operations schedule needs. A long purging time limits traffic; a short purging time may necessitate very high ventilation airflow rates, and result in high electrical energy demand and consumption. Consequently, multiple factors must be considered, including the overall ventilation concept, when establishing the purge rate.

PARKING GARAGES

Automobile parking garages can be either fully enclosed or partially open. Fully enclosed parking areas are often underground and require mechanical ventilation. Partially open parking garages are generally above-grade structural decks having open sides (except for barricades), with a complete deck above. Natural ventilation, mechanical ventilation, or a combination can be used for partially open garages.

Operating automobiles in parking garages presents two concerns. The more serious is emission of CO, with its known risks. The other concern is oil and gasoline fumes, which may cause nausea and headaches and also represent potential fire hazards. Additional concerns about NO_x and smoke haze from diesel engines may also require consideration. However, the ventilation rate required to dilute CO to acceptable levels is usually satisfactory to control the level of other contaminants as well, provided the percentage of diesel vehicles does not exceed 20%.

For many years, the various model codes, ANSI/ASHRAE *Standard* 62.1, and its predecessor standards recommended a flat exhaust rate of either 1.5 cfm/ft^2 or 6 ach for enclosed parking garages. But because vehicle emissions have been reduced over the years, ASHRAE sponsored a study to determine ventilation rates required to control contaminant levels in enclosed parking facilities (Krarti and Ayari 1998). The study found that, in some cases, much less ventilation than 1.5 cfm/ft^2 was satisfactory. The study's methodology for determining whether a reduced ventilation rate would be effective is included below. However, ANSI/ASHRAE *Standard* 62.1 and the International Code Council's *International Mechanical Code* (ICC 2003a) still require 1.5 cfm/ft^2 ventilation, whereas NFPA *Standard* 88A recommends a minimum of 1.0 cfm/ft^2, so the engineer may be required to request a variation, or waiver, from authorities having jurisdiction before implementing a lesser ventilation system design.

If larger fans are installed to meet code requirements, they will not necessarily increase overall power consumption; with proper CO level monitoring and ventilation system control, fans will run for shorter time periods to maintain acceptable CO levels. With increased attention on reducing energy consumption, CO-based ventilation system control can provide substantial cost savings in the operation of parking garages.

Ventilation Requirements and Design

ASHRAE Research Project RP-945 (Krarti and Ayari 1998) found that the design ventilation rate required for an enclosed parking facility depends chiefly on four factors:

- Acceptable level of contaminants in the parking facility
- Number of cars in operation during peak conditions
- Length of travel and the operating time for cars in the garage
- Emission rate of a typical car under various conditions

Contaminant Level Criteria. ACGIH (1998) recommends a threshold CO limit of 25 ppm for an 8 h exposure, and the U.S. EPA (2000) determined that exposure, at or near sea level, to a CO concentration of 35 ppm for up to 1 h is acceptable. For parking garages more than 3500 ft above sea level, more stringent limits are required. The ICC's (2003a) *International Mechanical Code* requires ventilation be provided to limit CO concentrations to 25 ppm or below.In Europe, an average concentration of 35 ppm and a maximum level of 200 ppm are usually maintained in parking garages.

Various agencies and countries differ on the acceptable level of CO in parking garages, but a reasonable solution is a ventilation rate designed to maintain a CO level of 35 ppm for 1 h exposure, with a maximum of 120 ppm, or 25 ppm for an 8 h exposure. Because the time associated with driving in and parking, or driving out of a garage, is on the order of minutes, 35 ppm is probably an acceptable level of exposure. However, Figure 14 provides nomographs for 15

LIVE GRAPH
Click here to view

CO_{max} = 15 ppm

LIVE GRAPH
Click here to view

CO_{max} = 25 ppm

LIVE GRAPH
Click here to view

CO_{max} = 35 ppm

| —— 2 min | —·—·— 1 min | ·········· 30 s |
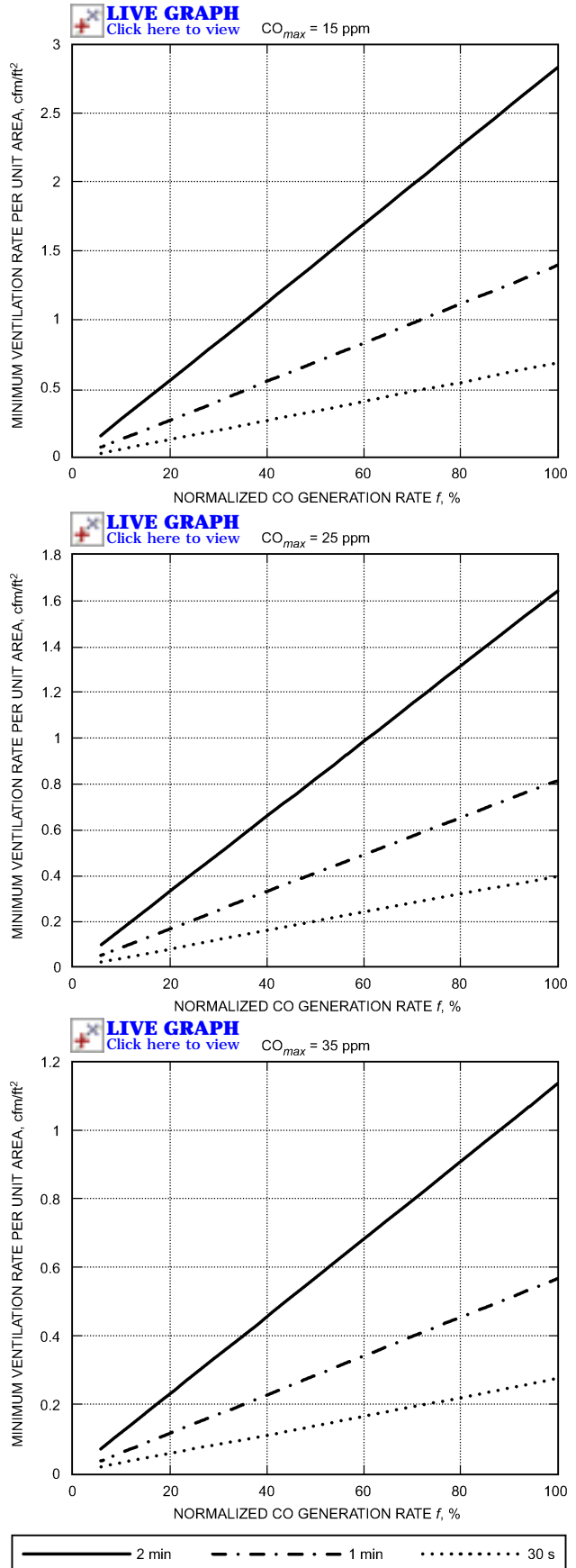
Fig. 14 Ventilation Requirement for Enclosed Parking Garage

and 25 ppm maximum exposures as well, to allow the designer to conform to more stringent regulations.

Number of Cars in Operation. The number of cars operating at any one time depends on the type of facility served by the parking garage. For distributed, continuous use, such as an apartment building or shopping area, the variation is generally 3 to 5% of the total vehicle capacity. The operating capacity could reach 15 to 20% in other facilities, such as sports stadiums or short-haul airports.

Length of Time of Operation. The length of time that a car remains in operation in a parking garage is a function of the size and layout of the garage, and the number of cars attempting to enter or exit at a given time. The operating time could vary from as much as 60 to 600 s, but on average, it usually ranges from 60 to 180 s. Table 7 lists approximate data for average vehicle entrance and exit times; this data should be adjusted to suit the specific physical configuration of the facility.

Car Emission Rate. Operating a car in a parking garage differs considerably from normal vehicle operation, including that in a road tunnel. Most car movements in and around a parking garage occur in low gear. A car entering a garage travels slowly, but the engine is usually hot. As a car exits from a garage, the engine is usually cold and operating in low gear, with a rich fuel mixture. Emissions for a cold start are considerably higher, so the distinction between hot and cold emission plays a critical role in determining the ventilation rate. Motor vehicle emission factors for hot- and cold-start operation are presented in Table 8. An accurate analysis requires correlation of CO readings with the survey data on car movements (Hama et al. 1974); the data should be adjusted to suit the specific physical configuration of the facility and the design year.

Design Method. To determine the design airflow rate required to ventilate an enclosed parking garage, the following procedure can be followed:

Step 1. Collect the following data:

- Number of cars N in operation during peak hour use
- Average CO emission rate E for a typical car, lb/h
- Average length of operation and travel time θ for a typical car, s
- Acceptable CO concentration CO_{max} in the garage, ppm
- Total floor area of parking facility A_f, ft^2

Step 2. Evaluate CO generation rate:

(1) Determine the peak CO generation rate per unit floor area G, in lb/h·ft^2, for the parking garage:

$$G = NE/A_f \qquad (16)$$

(2) Normalize the peak CO generation rate using the reference value $G_0 = 5.46 \times 10^{-3}$ lb/h·ft^2 and Equation (17). This reference value is based on an actual enclosed parking facility (Krarti and Ayari 1998):

$$f = 100G/G_0 \qquad (17)$$

Step 3. Determine the minimum required ventilation rate Q per unit floor area using Figure 14, or the correlation presented by Equation (18), depending on CO_{max}:

$$Q = Cf\theta \qquad (18)$$

where
$C = 2.370 \times 10^{-4}$ cfm/ft^2·s for $CO_{max} = 15$ ppm
$\ \ = 1.363 \times 10^{-4}$ cfm/ft^2·s for $CO_{max} = 25$ ppm
$\ \ = 0.948 \times 10^{-4}$ cfm/ft^2·s for $CO_{max} = 35$ ppm

Example 1. Consider a two-level enclosed parking garage with a total capacity of 450 cars, a total floor area of 90,000 ft^2, and an average height of 9 ft. The total length of time for a typical car operation is 2 min (120 s). Determine the required ventilation rate for the enclosed parking garage in cfm/ft^2 and in air changes per hour so that the CO level never exceeds 25 ppm. Assume that the number of cars in operation during peak use is 40% of the total vehicle capacity.

Step 1. Garage data:

$N = 450 \times 0.4 = 180$ cars

$E = 1.544$ lb/h, the average of all values of emission rate for a winter day, from Table 8

$CO_{max} = 25$ ppm

$\theta = 120$ s

Step 2. Calculate the normalized CO generation rate:

$G = (180 \times 1.544$ lb/h$)/90,000$ ft$^2 = 3.09 \times 10^{-3}$ lb/h·ft^2

$f = 100 \times (3.09 \times 10^{-3}$ lb/h·ft$^2) / 5.46 \times 10^{-3}$ lb/h·ft$^2 = 56.6$

Step 3. Determine the ventilation requirement, using Figure 14 or the correlation of Equation (18) for $CO_{max} = 25$ ppm.

$Q = 1.363 \times 10^{-4}$ cfm/s·ft$^2 \times 56.6 \times 120$ s $= 0.93$ cfm/ft^2

Or, for air changes per hour,

$(0.93$ cfm/ft$^2 \times 60$ min/h$)/9$ ft $= 6.2$ ach

Notes:

1. If the average vehicle CO emission rate is reduced to $E = 0.873$ lb/h, because of, for instance, better emission standards or better maintained cars, the required minimum ventilation rate decreases to 0.52 cfm/ft^2 or 3.5 ach.

2. Once calculations are made and a decision reached to use CO demand ventilation control, increasing airflow through a safety margin does not increase operating costs; larger fans work for shorter periods to sweep the garage and maintain satisfactory conditions.

CO Demand Ventilation Control. Whether mechanical, natural, or both, a parking garage ventilation system should meet applicable codes and maintain acceptable contaminant levels. If permitted by local codes, the ventilation airflow rate should be varied according to CO levels to conserve energy. For example, the ventilation system could consist of multiple fans, with single- or two-speed motors, or variable-pitch blades. In multilevel parking garages or single-level structures of extensive area, independent fan systems with individual controls are preferred. The *International Mechanical Code* (ICC 2003a) allows ventilation system operation to be reduced from 1.5 to 0.05 cfm/ft^2 with the use of a CO monitoring system that restores full ventilation when CO levels of 25 ppm are detected. Figure 15 shows the maximum CO level in a tested parking garage (Krarti and Ayari 1998) for three car movement profiles (Figure 16) and the following ventilation control strategies:

- Constant-volume (CV), where the ventilation system is kept on during the entire occupancy period
- On/off control, with fans stopped and started based on input from CO sensors

Table 7   Average Entrance and Exit Times for Vehicles

Level	Average Entrance Time, s	Average Exit Time, s
1	35	45
3*	40	50
5	70	100

Source: Stankunas et al. (1980).   *Average pass-through time = 30 s.

Table 8   Predicted CO Emissions in Parking Garages

Season	Hot Emission (Stabilized), lb/h		Cold Emission, lb/h	
	1991	1996	1991	1996
Summer, 90°F	0.336	0.250	0.565	0.484
Winter, 32°F	0.478	0.447	2.744	2.508

Results from EPA MOBILE3, version NYC-2.2 (1984); sea level location.
Note: Assumed vehicle speed is 5 mph.

- Variable-air-volume (VAV) control, using either two-speed fans or axial fans with variable-pitch blades, based on input from CO sensors

Figure 15 also shows typical fan energy savings achieved by on/off and VAV systems relative to constant-volume systems. Significant fan energy savings can be obtained using a CO-based demand ventilation control strategy to operate the ventilation system, maintaining CO levels below 25 ppm. Wear and tear and maintenance on mechanical and electrical equipment are reduced with a CO-based demand strategy.

Figure 16 is based on maintaining a 25 ppm CO level. With most systems, actual energy usage is further reduced if 35 ppm is maintained.

In cold climates, the additional cost of heating makeup air is also reduced with a CO-based demand strategy. Energy stored in the mass of the structure usually helps maintain the parking garage air temperature at an acceptable level. If only outside air openings are used to draw in ventilation air, or if infiltration is allowed, the stored energy is lost to the incoming cold air.

Ventilation System Configuration. Parking garage ventilation systems can be classified as supply-only, exhaust-only, or combined. Regardless of which system design is chosen, the following elements should be considered in planning the system configuration:

- Accounting for the contaminant level of outside air drawn in for ventilation
- Avoiding short-circuiting supply air
- Avoiding a long flow field that allows contaminants to exceed acceptable levels at the end of the flow field

Fig. 15   Typical Energy Savings and Maximum CO Level Obtained for Demand CO-Ventilation Controls

Fig. 16   Three Car Movement Profiles

- Providing short flow fields in areas of high contaminant emission, thereby limiting the extent of mixing
- Providing efficient, adequate airflow throughout the structure
- Accounting for stratification of engine exhaust gases when stationary cars are running in enclosed facilities

Other Considerations. Access tunnels or long, fully enclosed ramps should be designed in the same way as road tunnels. When natural ventilation is used, wall openings or free area should be as large as possible. Part of the free area should be at floor level.

For parking levels with large interior floor areas, a central emergency smoke exhaust system should be considered for removing smoke (in conjunction with other fire emergency systems) or vehicle fumes under normal conditions.

Noise. In general, parking garage ventilation systems move large quantities of air through large openings without extensive ductwork. These conditions, and the highly reverberant nature of the space, contribute to high noise levels, so sound attenuation should be considered in the ventilation system design. This is a pedestrian safety concern, as well, because high fan noise levels in a parking garage may mask the sound of an approaching vehicle.

Ambient Standards and Contaminant Control. Air exhausted from a parking garage should meet state and local air pollution control requirements.

AUTOMOTIVE REPAIR FACILITIES

Automotive repair activities are defined as any repair, modification, service, or restoration activity to a motor vehicle. This includes, but is not limited to, brake work, engine work, machining operations, and general degreasing of engines, motor vehicles, parts, or tools.

ANSI/ASHRAE *Standard* 62.1 recommends a ventilation rate of 1.5 cfm/ft^2 for automotive service stations. The high ventilation rate indicates that the contaminants are not related to the occupants, but are produced by the variety of tasks and materials used in the facility. Outdoor ventilation is introduced into the space and an amount approximately equal quantity is exhausted through a dedicated exhaust system.

As repairs or maintenance are performed on vehicles, it may be necessary to operate the vehicle inside the facility to test and validate the work. Additional mechanical ventilation is required to exhaust combustion by-products directly outdoors. An independent source capture system that connects directly to the exhaust pipe of the vehicle must be installed in the facility. These systems are available in either an above- or belowground configuration. Flow rates for individual service bays vary from 50 to 400 cfm for automobiles. A large diesel truck will require considerably more airflow per service bay than an automobile.

The above-grade system consists of an exhaust fan, associated ductwork, and flexible hoses that attach to the tailpipe of the vehicle in operation. Generally, the system is installed at a high elevation to maintain maximum clearances above floor level. The hose connections are stored in reels positioned near each service bay. The service technician pulls the hose down and attaches it to the tailpipe by a proprietary connection.

The below-grade system is similar in design to an overhead exhaust system. Care must be taken to select an appropriate corrosion-resistant material to be installed underground, because the condensing products of combustion are corrosive to traditional duct materials. The flexible tailpipe exhaust connectors are stored inside the underground duct. After sliding the flex back inside the duct, a hinged cover plate covers the opening flush to the floor.

Although there is a diversity factor in the system capacity calculations, both systems must be designed to operate at 100% capacity. A constant-volume fan is used, with all air being exhausted from the space. With a single outlet in use, some means of relief is provided to maintain constant flow through the fan. This equipment can be set
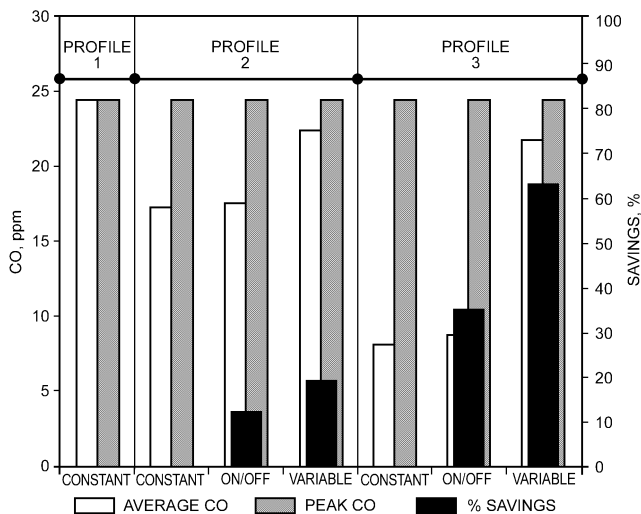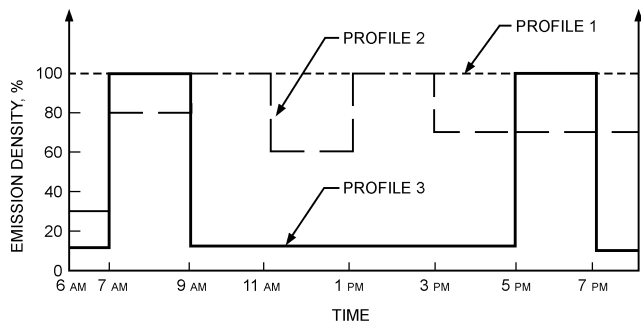
up to run continuously or intermittently. Intermittent use requires the general exhaust system to vary between the maximum supply air delivered to the space when the capture system is in use and a lower exhaust flow rate reduced by the amount of air exhausted through the capture system.

BUS GARAGES

Bus garages generally include a maintenance and repair area, service lane (where buses are fueled and cleaned), storage area (where buses are parked), and support areas such as offices, stock room, lunch room, and locker rooms. The location and layout of these spaces can depend on factors such as local climate, size of the bus fleet, and type of fuel used by the buses. Bus servicing and storage areas may be located outside in a temperate region, but are often inside in colder climates. However, large bus fleets cannot always be stored indoors; for smaller fleets, maintenance areas may double as storage space. Local building and/or fire codes may also prohibit dispensing certain types of fuel indoors.

In general, bus maintenance or service areas should be ventilated using 100% outside air with no recirculation. Therefore, using heat recovery devices should be considered in colder climates.

Tailpipe emissions should be exhausted directly from buses at fixed inspection and repair stations in maintenance areas. Offices and similar support areas should be kept under positive pressure to prevent infiltration of bus emissions.

Maintenance and Repair Areas

ANSI/ASHRAE *Standard* 62.1 and the *International Mechanical Code* (ICC 2003a) recommend minimum outdoor air ventilation of 1.5 cfm/ft^2 of floor area in vehicle repair garages, with no recirculation. However, because the interior ceiling height may vary greatly from garage to garage, the designer should consider making a volumetric analysis of contaminant generation and air exchange rates. The section on Bus Terminals contains information on diesel engine emissions and ventilation airflow rates needed to control contaminant concentrations in areas where buses are operated.

Maintenance and repair areas often include below-grade inspection and repair pits for working underneath buses. Because vapors produced by conventional bus fuels are heavier than air, they tend to settle in these pit areas, so a separate exhaust system should be provided to prevent their accumulation. NFPA *Standard* 30A recommends a minimum of 1 cfm/ft^2 in pit areas and the installation of exhaust registers near the floor of the pit.

Fixed repair stations, such as inspection/repair pits or hydraulic lift areas, should include a direct exhaust system for tailpipe emissions. Such direct exhaust systems have a flexible hose and coupling attached to the bus tailpipe; emissions are discharged to the outdoors by an exhaust fan. The system may be of the overhead reel, overhead tube, or underfloor duct type, depending on the tailpipe location. For heavy diesel engines, a minimum exhaust rate of 600 cfm per station is recommended to capture emissions without creating excessive backpressure in the vehicle. Fans, ductwork, and hoses should be able to receive vehicle exhaust at temperatures exceeding 500°F without degradation.

Bus garages often include areas for battery charging, which can produce potentially explosive concentrations of corrosive, toxic gases. There are no published code requirements for ventilating battery-charging areas, but DuCharme (1991) suggested using a combination of floor and ceiling exhaust registers to remove gaseous by-products. The recommended exhaust rates are 2.25 cfm/ft^2 of room area at floor level to remove acid vapors, and 0.75 cfm/ft^2 of room area at ceiling level, to remove hydrogen gases. The associated supply air volume should be 10 to 20% less than exhaust air volume, but designed to provide a minimum terminal velocity of 100 fpm at floor level. If the battery-charging space is located in the

general maintenance area rather than in a dedicated space, an exhaust hood should be provided to capture gaseous by-products. Chapter 30 contains specific information on exhaust hood design. Makeup air should be provided to replace that removed by the exhaust hood.

Garages may also contain spray booths, or rooms for painting buses. Most model codes reference NFPA *Standard* 33 for spray booth requirements; this standard should be reviewed when designing heating and ventilating systems for such areas.

Servicing Areas

For indoor service lanes, ANSI/ASHRAE *Standard* 62.1 and the *International Mechanical Code* (ICC 2003a) recommend a minimum ventilation rate of 1.5 cfm/ft^2, whereas NFPA *Standard* 30A recommends 1 cfm/ft^2. The designer should determine which minimum volume of ventilation air is applicable, based on the local code adopted. However, additional ventilation may be necessary: during a service cycle, buses often queue up in the service lane with their engines running. Depending on the queue length and service time for each bus, contaminant levels may exceed maximum allowable concentrations. Volumetric analysis examining contaminant generation should therefore be considered.

Because of the increased potential for concentrations of flammable or combustible vapor, HVAC systems for bus service lanes should not be interconnected with systems serving other parts of the bus garage. Service-lane HVAC systems should be interlocked with fuel-dispensing equipment, to prevent operation of the latter if the former is shut off or fails. Exhaust inlets should be located both at ceiling level and 3 to 12 in. above the finished floor, with supply and exhaust diffusers/registers arranged to provide air movement across all planes of the dispensing area. A typical equipment arrangement is shown in Figure 17.

Another feature in some service lanes is the cyclone cleaning system: these devices have a dynamic connection to the front door(s) of the bus, through which a large-volume fan vacuums dirt and debris from inside the bus. A large cyclone assembly then removes dirt and debris from the airstream and deposits it into a large hopper for disposal. Because of the large volume of air involved, the designer should consider the discharge and makeup air systems required to complete the cycle. Recirculation and energy recovery should be considered, especially during winter. To aid in contaminant and heat removal during summer, some systems discharge the cyclone air to the outside and provide untempered makeup air through relief hoods above the service lane.
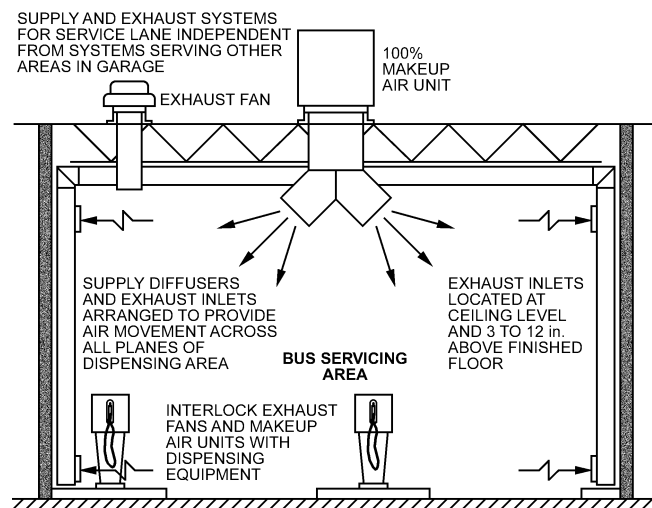
Fig. 17 Typical Equipment Arrangement for Bus Garage

Storage Areas

Where buses are stored inside, the minimum ventilation standard of 1.5 cfm/ft^2 should be provided, subject to volumetric considerations. The designer should also consider the increased contaminant levels present during peak traffic periods.

One example is morning pullout, when the majority of the fleet is dispatched for rush-hour commute. It is common practice to start and idle a large number of buses during this period to warm up the engines and check for defects. As a result, the emissions concentration in the storage area rises, and additional ventilation may be required to maintain contaminant levels in acceptable limits. Using supplemental purge fans is a common solution to this problem. These purge fans can either be (1) interlocked with a timing device to operate during peak traffic periods, (2) started manually on an as-needed basis, or (3) connected to an air quality monitoring system that activates them when contaminant levels exceed some preset limit.

Design Considerations and Equipment Selection

Most model codes require that open-flame heating equipment, such as unit heaters, be located at least 8 ft above the finished floor or, where located in active trafficways, 2 ft above the tallest vehicle. Fuel-burning equipment outside the garage area, such as boilers in a mechanical room, should be installed with the combustion chamber at least 18 in. above the floor. Combustion air should be drawn from outside the building. Exhaust fans should be nonsparking, with their motors located outside the airstream.

Infrared heating systems and air curtains are often considered for bus repair garages because of the size of the facility and amount of infiltration through the large doors needed to move buses in and out of the garage. However, infrared heating must be used cautiously in areas where buses are parked or stored for extended periods, because the buses may absorb most of the heat, which is then lost when the buses leave the garage. This is especially true during morning pullout. Infrared heating can be applied with more success in the service lane, or at fixed repair positions. Air curtains should be considered for high-traffic doorways to limit both heat loss and infiltration of cold air.

Where air quality monitoring systems control ventilation equipment, maintainability is a key factor in determining success of the application. The high concentration of particulate matter in bus emissions can adversely affect monitoring equipment, which often has filtering media at sampling ports to protect sensors and instrumentation. The location of sampling ports, effects of emissions fouling, and calibration requirements should be considered when selecting monitoring equipment to control ventilation systems and air quality of a bus garage. NO$_2$ and CO exposure limits published by OSHA and the EPA should be consulted to determine contaminant levels at which exhaust fans should be activated.

Effects of Alternative Fuel Use

Because of legislation limiting contaminant concentrations in diesel bus engine emissions, the transportation industry has begun using buses that operate on alternative fuels, including methanol, ethanol, hydrogen (and fuel cells), compressed natural gas (CNG), liquefied natural gas (LNG), and liquefied petroleum gas (LPG). Flammability, emission, and vapor dispersion characteristics of these fuels differ from those of conventional fuels, for which current code requirements and design standards were developed. Thus, established ventilation requirements may not be valid for bus garage facilities used by alternative-fuel vehicles. The designer should consult current literature on HVAC system design for these facilities rather than relying on conventional practices. One source is the Alternative Fuels Data Center at the U.S. Department of Energy in Washington, D.C; their Web site (www.eere.energy.gov/afdc) includes design recommendations for various alternative fuels. The DOT (1996a, 1996b, 1996c, 1997b, 1998) Volpe Transportation Center has also issued several guidelines for alternative-fuel bus facilities, which can be consulted for additional suggestions.

CNG Vehicle Facilities. For CNG bus facilities, NFPA *Standard* 52 recommends a separate mechanical ventilation system providing at least 1 cfm per 12 ft^3, or 5 ach, for indoor fueling and gas processing/storage areas. The ventilation system should operate continuously, or be activated by a continuously monitoring natural gas detector when a gas concentration of not more than 20% of the lower flammability limit (LFL) is present. The fueling or fuel-compression equipment should be interlocked to shut down if the mechanical ventilation system fails. Supply inlets should be located near floor level; exhaust outlets should be located high in the roof or exterior wall structure. The *International Mechanical Code* (ICC 2003a) has identical requirements, except that it requires activation of the ventilation system at 25% of the LFL, and the requirements apply to maintenance and repair areas as well as indoor fueling facilities.

DOT (1996a) guidelines for CNG facilities address bus storage and maintenance areas, as well as bus fueling areas. DOT recommendations include (1) minimizing potential for dead-air zones and gas pockets (which may require coordination with architectural and structural designers); (2) using a normal ventilation rate of 6 ach, with provisions to increase that rate by an additional 6 ach in the event of a gas release; (3) using nonsparking exhaust fans rated for use in Class 1, Division 2 areas (as defined by NFPA *Standard* 70); and (4) increasing the minimum ventilation rate in smaller facilities to maintain dilution levels similar to those in larger facilities. Open-flame heating equipment should not be used, and the surface temperature of heating units should not exceed 800°F. In the event of a gas release, deenergizing supply fans that discharge near the ceiling level should be considered, to avoid spreading the gas plume.

LNG Vehicle Facilities. The 2006 edition of NFPA *Standard* 57 includes requirements for LNG bus facilities. The standard recommends a separate mechanical ventilation system providing at least 1 cfm per 12 ft^3, or 5 ach, for indoor fueling areas. The ventilation system should operate continuously, or be activated by a continuously monitoring natural gas detection system when a gas concentration of not more than 20% of the LFL is present. Fueling equipment should be interlocked to shut down in case the mechanical ventilation system fails. DOT (1997b) provides further information on LNG fuel.

LPG Vehicle Facilities. NFPA *Standard* 58 and the *International Fuel Gas Code* (ICC 2003b) contain similar provisions relating specifically to LPG-fueled vehicles. Both standards prohibit indoor fueling of all LPG vehicles, allowing only an adequately ventilated weather shelter or canopy for fueling operations. However, the term "adequately ventilated" is not defined by any prescriptive rate. Vehicles are permitted to be stored and serviced indoors under NFPA *Standard* 58, provided they are not parked near sources of heat, open flames (or similar sources of ignition), or "inadequately ventilated" pits. That standard does not recommend a ventilation rate for bus repair and storage facilities, but it does recommend a minimum of 1 cfm/ft^2 in buildings and structures housing LPG distribution facilities. DOT (1996b) provides additional information on LPG fuel.

Hydrogen Vehicle Facilities. The 2006 edition of NFPA *Standard* 52 includes requirements for gaseous and liquid hydrogen bus facilities. The standard recommends a separate mechanical ventilation system providing at least 1 cfm/ft^2, but not less than 1 cfm per 12 ft^3, or 5 ach, for indoor gaseous hydrogen fueling areas. The ventilation system should operate continuously, or be activated by a continuously monitoring natural gas detection system when a gas concentration of not more than 25% of the LFL is present. Fueling equipment should be interlocked to shut down in case the mechanical ventilation system fails. Liquid hydrogen fueling facilities are prohibited indoors. The *International Mechanical Code* (ICC 2003a) has the same requirements, which apply to maintenance and repair areas as well as indoor fueling facilities. DOT (1998) provides additional information on hydrogen fuel.

BUS TERMINALS

The physical configuration of bus terminals varies considerably. Most terminals are fully enclosed spaces containing passenger waiting areas, ticket counters, and some retail areas. Buses load and unload outside the building, generally under a canopy for weather protection. In larger cities, where space is at a premium and bus service is extensive or integrated with subway service, bus terminals may have comprehensive customer services and enclosed (or semi-enclosed) multilevel structures, busway tunnels, and access ramps.

Waiting rooms and consumer spaces should have controlled environments in accordance with normal HVAC system design practices for public terminal occupancies. In addition to providing the recommended ventilation air rate in accordance with ANSI/ASHRAE *Standard* 62.1, the space should be pressurized against infiltration from the busway environment. Pressurized vestibules should be installed at each doorway to further reduce contaminant migration and to maintain acceptable air quality. Waiting rooms, passenger concourse areas, and platforms are typically subjected to a highly variable people load. The average occupant density may reach 10 ft^2 per person and, during periods of extreme congestion, 3 to 5 ft^2 per person.

The choice between natural and mechanical ventilation should be based on the physical characteristics of the bus terminal and the airflow required to maintain acceptable air quality. When natural ventilation is selected, the individual levels of the bus terminal should be open on all sides, and the slab-to-ceiling dimension should be sufficiently high, or the space contoured, to allow free air circulation. Jet fans can be used to improve natural airflow in the busway, with relatively low energy consumption. Mechanical systems that ventilate open platforms or gate positions should be configured to serve bus operating areas, as shown in Figures 18 and 19.

Platforms

Platform design and orientation should be tailored to expedite passenger loading and unloading, to minimize both passenger exposure to the busway environment and dwell time of an idling bus in an enclosed terminal. Naturally ventilated drive-through platforms may expose passengers to inclement weather and strong winds. An enclosed platform (except for an open front), with the appropriate mechanical ventilation system, should be considered.
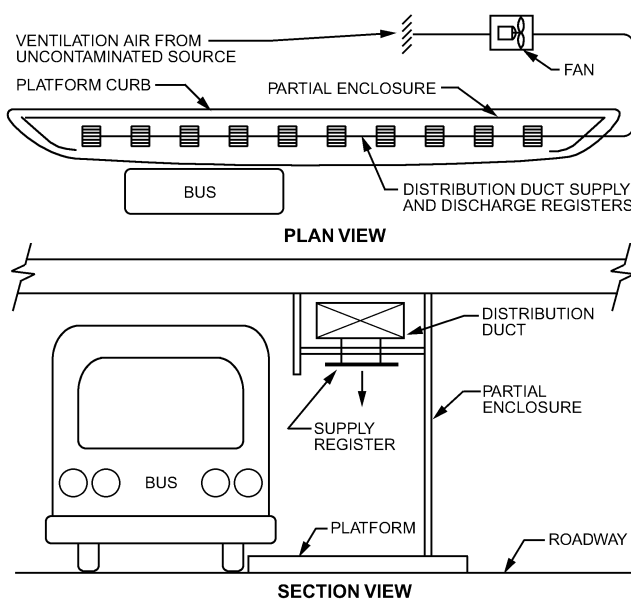
Partially enclosed platforms can trap contaminants and may require mechanical ventilation to achieve acceptable air quality.

Multilevel bus terminals have limited headroom, which restricts natural ventilation system performance. These terminals should have mechanical ventilation, and all platforms should be either partially or fully enclosed. The platform ventilation system should not induce contaminated airflow from the busway environment. Supply air velocity should also be limited to 250 fpm to avoid drafts on the platform. Partially enclosed platforms require large amounts of outside air to hinder fume penetration; experience indicates that a minimum of 17 cfm per square foot of platform area is typically required during rush hours, and about half this rate is required during other periods. Figure 18 shows a partially enclosed drive-through platform with an air distribution system.

Platform air quality should remain essentially the same as that of the ventilation air introduced. Because of the piston effect, however, some momentarily high concentrations of contaminants may occur on the platform. Separate ventilation systems with two-speed fans (for each platform) allow operational flexibility, in both fan usage frequency and supply airflow rate for any one platform. Fans should be controlled automatically to conform to bus operating schedules. In cold climates, mechanical ventilation may need to be reduced or heated during extreme winter weather conditions.

For large terminals with heavy bus traffic, fully enclosed platforms are strongly recommended. Fully enclosed platforms can be adequately pressurized and ventilated with normal heating and cooling air quantities, depending on the construction tightness and number of boarding doors and other openings. Conventional air distribution can be used; air should not be recirculated. Openings around doors and in the enclosure walls are usually adequate to relieve air pressure, unless the platform construction is extraordinarily tight. Figure 19 shows a fully enclosed waiting room with sawtooth gates.

Doors between sawtooth gates and the waiting room should remain closed, except for passenger loading and unloading. The

Fig. 18   Partially Enclosed Platform, Drive-Through Type
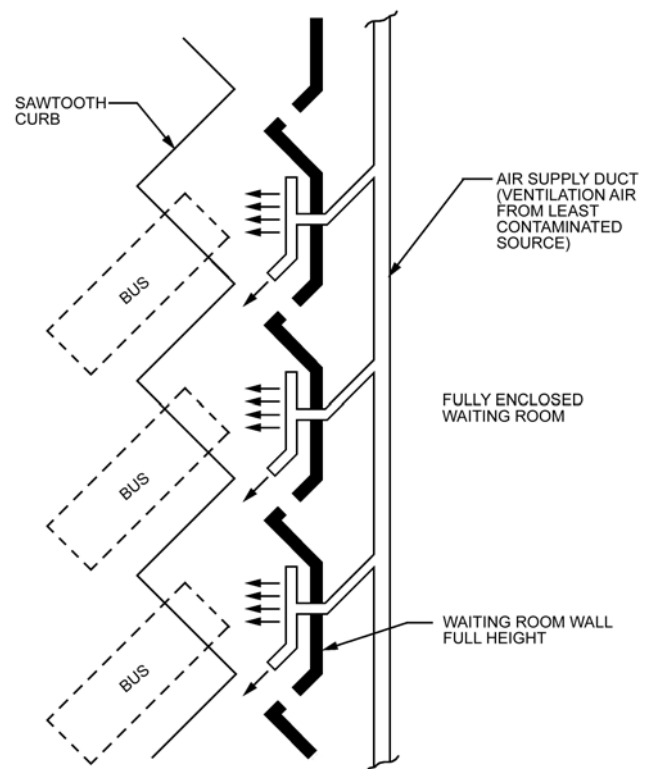
Fig. 19   Fully Enclosed Waiting Room with Sawtooth Gates

waiting room ventilation system should provide positive pressurization to minimize infiltration of contaminants from the busway environment. Supply air from a suitable source should be provided at the passenger boarding area for each gate to dilute local contaminants to acceptable levels.

Bus Operation Areas

Ventilation for bus operation areas should be designed and evaluated to maintain engine exhaust contaminant concentrations within the limits set by federal and local regulations and guidelines. With the proliferation of alternative fuels, such as biodiesel, ethanol, methanol, compressed natural gas (CNG), and liquefied natural gas (LNG), a bus terminal ventilation system should not only be designed for maintaining acceptable air quality, but should also consider the safety risks associated with potential leakage from buses operating with alternative fuel loads. In an enclosed or semienclosed area, a comprehensive risk assessment should be performed for the specific types of buses operating in the bus terminal. The nature of the bus engines should be determined for each project.

Contaminants. Of all the different types of buses in operation, engine exhaust from diesel buses has the most harmful quantities of contaminants. Some diesel buses also have small auxiliary gasoline engines to drive the vehicle air-conditioning system. Excessive exposure to diesel exhaust can cause adverse health effects, ranging from headache and nausea to cancer and respiratory disease. Tests on the volume and composition of exhaust gases emitted from diesel engines during various traffic conditions indicate large variations depending on the (1) local air temperature and humidity; (2) manufacturer, size, and adjustment of the engine; and (3) type of fuel used.

Components of diesel engine exhaust gases that affect the ventilation system design are NO_x, hydrocarbons, formaldehyde, odor constituents, aldehydes, smoke particles, sulfur dioxide, and a relatively small amount of CO. Diesel engines operating in enclosed spaces also reduce visibility, and generate both odors and particulate matter.

Table 9 lists major health-threatening contaminants found in diesel engine exhaust and the exposure limits set by OSHA and ACGIH.

OSHA permissible exposure limits (PEL) are legally enforceable limits, whereas the ACGIH threshold limit values (TLV) are industrial hygiene recommendations. All the limits are time-weighted averages (TWAs) for 8 h exposure, unless noted as a ceiling value.

NO_x occurs in two basic forms: nitrogen dioxide (NO_2) and nitric oxide (NO). NO_2 is the major contaminant considered in bus terminal ventilation system design. Prolonged exposure to NO_2 concentrations of more than 5 ppm causes health problems. Furthermore, NO_2 affects light transmission and thereby reduces visibility. NO_2 is intensely colored and absorbs light over the entire visible spectrum, especially at shorter wavelengths. Odor perception of NO_2 is

immediate at 0.42 ppm, but can be perceived by some at levels as low as 0.12 ppm.

Bus terminal operations also affect the quality of surrounding ambient air. The ventilation airflow rate, contaminant levels in exhaust air, and location and design of the air intakes and discharges determine the effect of the bus terminal on local ambient air quality.

State and local regulations, which require consideration of local atmospheric conditions and ambient contaminant levels in bus terminal ventilation system design, must be followed.

Calculation of Ventilation Rate

To calculate the ventilation rate, the total amount of engine exhaust gases should be determined using the bus operating schedule and amount of time that the buses are in various modes of operation (i.e., cruising, decelerating, idling, and accelerating). The designer must ascertain the grade (if any) in the terminal, and whether platforms are drive-through, drive-through with bypass lanes, or sawtooth. Bus headway, bus speed, and various platform departure patterns must also be considered. For instance, with sawtooth platforms, the departing bus must accelerate backward, brake, and then accelerate forward. The drive-through platform requires a different pattern of departure.

Certain codes prescribe a maximum idling time for bus engines, usually 3 to 5 min. Normally, 1 to 2 min of engine operation is required to build up brake air pressure. EPA emission standards for urban bus engines are summarized in Table 10 (bus emission standards in the state of California are more restrictive). The latest version of the EPA emission factor algorithm should be used to estimate bus tailpipe emissions. The current recommended version is MOBILE6.2 (2002), but a new model, MOVES, is being tested by the EPA and will be used in the future. Input parameters (e.g., local vehicular inspection and maintenance requirements) suitable for a specific facility should be obtained from the appropriate air quality regulatory agency.

Discharged contaminant quantities should be diluted by natural and/or mechanical ventilation to accepted, legally prescribed levels. To maintain odor control and visibility, exhaust gas contaminants should be diluted with outside air in the proportion 75 to 1.

Where urban-suburban bus operations are involved, the ventilation rate varies considerably throughout the day, and also between weekdays and weekends. Fan speed or blade pitch control should be used to conserve energy. The required ventilation airflow may be reduced by removing contaminant emissions as quickly as possible. This can be achieved by mounting exhaust capture hoods in the terminal ceiling, above each bus exhaust stack. Exhaust air collected by the hoods is then discharged outside of the facility through a dedicated exhaust system.

Effects of Alternative Fuel Use. As discussed in the section on Bus Garages, alternative fuels are being used more widely in lieu of

Table 9 8 h TWA Exposure Limits for Gaseous Pollutants from Diesel Engine Exhaust, ppm

Substance	OSHA PEL	ACGIH TLV
Carbon monoxide (CO)	50	25
Carbon dioxide (CO_2)	5000	5000
Nitric oxide (NO)	25	25
Nitrogen dioxide (NO_2)	5.0*	3.0
Formaldehyde (HCHO)	0.75	0.30*
Sulfur dioxide (SO_2)	5.0	2.0

*Ceiling value
Note: For data on diesel bus and truck engine emissions, see Watson et al. (1988).

Table 10 EPA Emission Standards for Urban Bus Diesel Engines

| Model Year | Emissions, lb/min·bhp × 10⁻⁵ | | | |
	Hydrocarbons (HC)	Carbon Monoxide (CO)	Oxides of Nitrogen (NO_x)	Particulate Matter (PM)
1991	4.78	57.0	18.4	0.919
1993	4.78	57.0	18.4	0.368
1994	4.78	57.0	18.4	0.257
1996	4.78	57.0	18.4	0.184*
1998 to 2003	4.78	57.0	14.7	0.184*
2004 to 2006	4.78	57.0	7.35 to 9.19	0.184
2007 and later	0.515	57.0	0.074	0.037

*In-use PM standard 0.257×10^{-5} lb/min·bhp

conventional diesel fuel, especially for urban-suburban bus routes, as opposed to long-distance bus service.

Current codes and design standards developed for conventional fuels may not be valid for alternative-fuel buses. Comprehensive design guidelines are not yet available; there is a lack of design standards and long-term safety records for the alternative-fuel buses and their components. Special attention should be given to both risk assessment and design of HVAC and electrical systems for these facilities with regard to a fuel tank or fuel line leak. Research is continuing in this application; further information may be available from the DOT Volpe Transportation Center and NFPA *Standards* 52 and 58.

Bus terminal design should include a risk assessment to review terminal operations and identify potential hazards from alternative fuel buses. Facility managers should adopt safety principles to determine the acceptability of these hazards, based on severity and frequency of occurrence. All hazards deemed undesirable or unacceptable should be eliminated by system design, or by modifications to operations.

Natural Gas (NG) Buses. Fuel burned in LNG and CNG buses has a composition of up to 98% methane (CH_4). Methane burns in a self-sustained reaction only when the volume percentage of fuel and air is in specific limits. The lower and upper flammability, or explosive, limits (LEL and UEL) for methane are 5.3% and 15.0% by volume, respectively. At standard conditions, the fuel/air mixture burns only in this range and in the presence of an ignition source, or when the spontaneous ignition temperature of 1003°F is exceeded.

Electrical and mechanical systems in a bus terminal facility should be designed to minimize the number of ignition sources at locations where an explosive natural gas mixture can accumulate.

Although emissions from an NG bus engine include unburned methane, design of the bus terminal ventilation system must be based on maintaining facility air quality below the LEL in the event of a natural gas leak. A worst-case scenario for natural gas accumulation in a facility is a leak from the bus fuel line or fuel tank, or a sudden high-pressure release of natural gas from a CNG bus fuel tank through its pressure relief device (PRD). For instance, a typical CNG bus may have multiple fuel tanks, each holding gas at 3600 psig and 70°F. If the PRD on a single tank were to open, the tank contents would escape rapidly. After 1 min, 50% of the fuel would be released to the surroundings, after 2 min, 80% would be released, and 90% would be released after 3 min.

Because such a large quantity of fuel is released so quickly, prompt activation of a ventilation purge mode is essential. Where installed, a methane detection system should activate a ventilation purge and an alarm at 20% of the LEL. Placement of methane detectors is very important; stagnant areas, bus travel lanes, and bus loading areas must be considered. In addition, although methane is lighter than air (the relative density of CH_4 is 0.55), some research indicates that it may not rise immediately after a leak. In a natural gas release from a PRD, the rapid throttle-like flow through the small-diameter orifice of the device may actually cool the fuel, making it heavier than air. Under these conditions, the fuel may migrate toward the floor until reaching thermal equilibrium with the surrounding environment; then, natural buoyancy forces will drive the fuel/air mixture to the ceiling. Thus, the designer may consider locating methane detectors at both ceiling and floor levels of the facility.

Although no specific ventilation criteria have been published for natural gas vehicles in bus terminals, NFPA *Standard* 52 recommends a blanket rate of 5 ach in fueling areas. DOT (1996) guidelines for CNG transit facility design recommend a slightly more conservative 6 ach for normal ventilation rates in bus storage areas, with capability for 12 ach ventilation purge rate (on activation by the methane sensors). The designer can also calculate a ventilation purge rate based on the volumetric flow rate of methane released, duration of the release, and size of the facility.

The size of the bus terminal significantly affects the volume flow of ventilation air required to maintain the average concentration of

methane below 10% of the LEL. The larger the facility, the lower the number of air changes required. However, a methane concentration that exceeds the LEL can be expected in the immediate area of the leak, regardless of the ventilation rate used. The size of the plume and location/duration of the unsafe methane concentration may be determined using comprehensive modeling analysis, such as computational fluid dynamics.

Source of Ventilation Air. Because dilution is the primary means of contaminant level control, the ventilation air source is extremely important. The cleanest available ambient air should be used for ventilation; in an urban area, the cleanest air is generally above roof level. Surveys of contaminant levels in ambient air should be conducted, and the most favorable source of ventilation air should be used. The possibility of short-circuiting exhaust air, because of prevailing winds and/or building airflow patterns, should also be evaluated.

If the only available ambient air has contaminant levels exceeding EPA ambient air quality standards, the air should be treated to control offending contaminants. Air-cleaning systems for removing gases, vapors, and dust should be installed to achieve necessary air quality.

Control by Contaminant Level Monitoring. Time clocks are one of the most practical means of controlling a bus terminal ventilation system. Time-clock-based ventilation control systems are typically coordinated with both bus movement schedules and installed smoke monitoring devices (i.e., obscurity meters). A bus terminal ventilation system can also be controlled by monitoring levels of individual gases, such as CO, CO_2, NO_2, methane, or other toxic or combustible gases.

Dispatcher's Booth. The bus dispatcher's booth should be kept under positive air pressure to prevent infiltration of engine exhaust fumes. Because the booth is occupied for sustained periods, both normal interior comfort conditions and minimum gas contaminant levels must be maintained during the hours of occupancy.

TOLLBOOTHS

Toll plazas for vehicular tunnels, bridges, and toll roads generally include a series of individual tollbooths. An overhead weather canopy and a utility tunnel (located below the roadway surface) are frequently provided for each toll plaza. The canopy allows installation of roadway signs, air distribution ductwork, and lighting. The utility tunnel is used to install electrical and mechanical systems; it also provides access to each tollbooth. An administration building is usually situated nearby. The current trend in toll collection facility design favors automatic toll collection methods that use magnetic tags. However, new and retrofit toll plazas still include a number of manual toll collection lanes with individual tollbooths.

Toll collectors and supervisors are exposed to adverse environmental conditions similar to those in bus terminals and underground parking garages. Automotive emission levels are considerably higher at a toll facility than on a highway because of vehicle deceleration, idling, and acceleration. Increased levels of CO, NO_x, diesel particulates, gasoline fumes, and other automotive emissions have a potentially detrimental effect on health.

Toll collectors cannot totally rely on physical barriers to isolate them from automotive emissions, because open windows are necessary for collecting tolls. Frequent opening and closing of the window makes the heating and cooling loads of each booth fluctuate independently. Heat loss or gain is extremely high, because all four sides (and frequently the ceiling) of the relatively small tollbooth are exposed to the outdoor ambient air temperature.

HVAC air distribution requirements for a toll facility should be carefully evaluated to maintain an acceptable environment inside the tollbooth and minimize the adverse ambient conditions to which toll-collecting personnel are exposed.

Air Quality Criteria

Workplace air quality standards are mandated by local, state, and federal agencies. Government health agencies differ on acceptable CO levels. ACGIH (1998) recommends a threshold limit of 25 ppm of CO for an 8 h exposure. OSHA (2001a) regulations are for 50 ppm for repeated daily 8 h exposure to CO in the ambient air. The U.S. National Institute for Occupational Safety and Health (NIOSH 1994) recommends maintaining an average of 35 ppm and a maximum level of 200 ppm. Criteria for maximum acceptable CO levels should be developed with the proper jurisdiction. As a minimum, the ventilation system should be designed to maintain CO levels below the threshold limit for an 8 h exposure. Deceleration, idling, and acceleration of vehicles, and varying traffic patterns make it difficult to estimate CO levels around specific toll-collecting facilities without using computer programs.

Longitudinal tunnel ventilation systems with jet fans or Saccardo nozzles are increasingly popular for vehicular tunnels with unidirectional traffic flow. These longitudinal ventilation systems discharge air contaminants from the tunnel through the exit portal. If toll plazas are situated near the exit portal, resultant CO levels around the facilities may be higher than for other toll facilities.

If a recirculating HVAC system were used for a toll collection facility, any contaminants entering a particular tollbooth would remain in the ventilation air. Therefore, tollbooth ventilation systems should distribute 100% outside air to each booth to prevent both intrusion and recirculation of airborne contaminants.

Design Considerations

The toll plaza ventilation system should pressurize booths to keep out contaminants emitted by traffic. Opening the window during toll collection varies depending on booth design and the habits of the individual toll collector. The amount of ventilation air required for pressurization similarly varies.

Variable-air-volume (VAV) systems that are achievable with controls now available can vary the air supply rate based on either the pressure differential between the tollbooth and the outdoor environment, or the position of the tollbooth window. A fixed (maximum/minimum) volume arrangement may also be used at toll plazas with a central VAV system.

Because the area of the window opening varies with individual toll collector habits and the booth architecture, the design air supply rate may be determined based on an estimated average window open area. The minimum air supply (when the booth window is closed) should be based on the amount of air required to meet the heating/cooling requirements of the booth, and that required to prevent infiltration of contaminants through the door and window cracks. Where the minimum supply rate exceeds the exfiltration rate, provisions to relieve excess air should be made to prevent overpressurization.

The space between the booth roof and the overhead canopy may be used to install individual HVAC units, fan-coil units, or VAV boxes. Air ducts and HVAC piping may be installed on top of the plaza canopy or in the utility tunnel. The ducts or piping should be insulated as needed.

The amount of ventilation air is typically high compared to the size of the booth; the resulting rate of air change is also high. Supply air outlets should be sized and arranged to deliver air at low velocity. Air reheating should be considered where the supply air temperature is considered too low.

In summer, the ideal air supply location is the ceiling of the booth, which allows cooler air to descend through the booth. In winter, the ideal air supply location is from the bottom of the booth, or at floor level. It is not always possible to design ideal distribution for both cooling and heating. When air is supplied from the ceiling, other means for providing heat at the floor level (such as electric forced-air heaters, electric radiant heating, or heating coils in the floor) should be considered.

The supply air intake should be located so that air drawn into the system is as free as practicable of vehicle exhaust fumes. The prevailing wind should be considered when locating the intake, which should be as far from the roadway as is practicable to provide better-quality ventilation air. Particle filtration of supply air for booths should be carefully evaluated. The specific level and type of filtering should be based on the ambient level of particulate matter and the desired level of removal. See Chapter 12 of the 2005 *ASHRAE Handbook—Fundamentals* and Chapter 24 in the 2004 *ASHRAE Handbook—HVAC Systems and Equipment* for more information.

Equipment Selection

Individual HVAC units and central HVAC are commonly used for toll plazas. Individual HVAC units allow each toll collector to choose between heating, cooling, or ventilation modes. Maintenance of individual units can be performed without affecting HVAC units in other booths. In contrast, a central HVAC system should have redundancy to avoid a shutdown of the entire toll plaza system during maintenance operations.

The design emphasis on booth pressurization requires using 100% outside air; high-efficiency air filters should therefore be considered. When a VAV system is used to reduce operating cost, varying the supply rate of 100% outside air requires a complex temperature control system that is not normally available for individual HVAC units. Individual HVAC units should be considered only where the toll plaza is small, or where the tollbooths are so dispersed that a central HVAC system is not economically justifiable.

Where hot-water, chilled-water, or secondary water service is available from an adjacent administration building, an individual fan-coil for each tollbooth and a central air handler for supplying the total volume of ventilation air may be economical. When the operating hours for the booths and administration building are significantly different, separate heating and cooling for the toll collecting facility should be considered. Central air distribution system selection should be based on the maximum number of open traffic lanes during peak hours and the minimum number of open traffic lanes during off-peak hours.

The HVAC system for a toll plaza is generally required to operate continuously. Minimum ventilation air may be supplied to unoccupied tollbooths to prevent infiltration of exhaust fumes. Otherwise, consideration should be given to remotely flushing the closed tollbooths with ventilation air before their scheduled occupancy.

DIESEL LOCOMOTIVE FACILITIES

Diesel locomotive facilities include shops where locomotives are maintained and repaired, enclosed servicing areas where supplies are replenished, and overbuilds where locomotives routinely operate inside an enclosed space and where railroad workers and/or train passengers may be present. In general, these areas should be kept under slightly negative air pressure to help removal of fumes and contaminants. Ventilation should use 100% outside air. However, recirculation may be used to maintain space temperature when a facility is unoccupied or when engines are not running. Heat recovery devices should be considered for facilities in colder climates, though they may require additional maintenance.

Historically, ventilation guidelines for locomotive facilities have recommended simple exhaust rates usually based on the volume of the facility. These were developed over many years of experience and were based on the assumption of nitrogen dioxide as the most critical contaminant. Because contaminant limits for constituents of diesel exhaust have been and are likely to continue changing, ASHRAE sponsored Research Project RP-1191 (Musser and Tan 2004), which included field measurements in several facilities and a

parametric study of design options using computational fluid dynamics. The study resulted in a simplified contaminant-based design procedure that allows designers flexibility to adapt to other critical contaminants or concentrations. Both the traditional and RP-1191 approaches are discussed here.

Ventilation Guidelines and Facility Types

Maintenance and Repair Areas. ANSI/ASHRAE *Standard* 62.1 and most model codes require a minimum outdoor air ventilation rate of 1.5 cfm/ft^2 in vehicle repair garages, with no recirculation recommended. Because the ceiling is usually high in locomotive repair shops, the designer should consider making a volumetric analysis of contaminant generation and air exchange rates rather than using the 1.5 cfm/ft^2 ventilation rate as a blanket standard. The section on Contaminants has more information on diesel engine exhaust emissions.

Information in the section on Bus Garages also applies to locomotive shops, especially for below-grade pits, battery charging areas, and paint spray booths. However, diesel locomotives generally have much larger engines (ranging to over 6000 hp) than buses. Ventilation is needed to reduce crew and worker exposure to exhaust gas contaminants, and to remove heat emitted from engine radiators. Where possible, diesel engines should not be operated in shops. Shop practices should restrict diesel engine activity and engine operating speeds/intervals; however, some shops require that locomotives be load-tested at high engine speeds. This should be done outdoors if possible, both to reduce indoor contaminants and to avoid problems associated with high heat (sprinkler activation, fire risk, etc.). A dedicated area should be established for diesel engine operations; hoods should be used to capture engine exhaust in this area. If hoods are impractical because of physical obstructions, then dilution ventilation must be used.

In designing hoods, the location of each exhaust point on each type of locomotive must be identified so that each hood can be centered and located as close as possible to each exhaust point. Local and state railroad clearance regulations must be followed, along with occupational safety requirements. In some cases, high ceilings or overhead cranes may limit hood use. Some newer systems attempt to avoid this problem by using a flexible connection that attaches to the exhaust. The hood design should not increase backpressure on locomotive exhaust; the throat velocity should be kept less than twice the exhaust discharge velocity. The associated duct design should include access doors and provisions for cleaning oily residue, which increases the risk of fire. Fans and other ventilation equipment in the airstream should be selected with regard to the elevated temperature of the exhaust air and the effects of the oily residue in the emissions.

Sometimes high ceilings or overhead cranes limit the use of hoods. The *Manual for Railway Engineering* (AREMA 2007) notes that 6 air changes per hour are usually sufficient to provide adequate dilution for both idling locomotives and short engine runs at high speed. This guideline was developed with nitrogen dioxide as the critical contaminant, with an allowable maximum concentration of 5 ppm(v). Even dilution systems can and should take advantage of thermal buoyancy by removing exhaust air at the ceiling level or a high point in the shop and introducing makeup air at floor level. If exhaust gases are allowed to cool and drop to floor level, locomotive radiator fans (if operating) can cause further mixing in the occupied zone, making removal less effective.

Shops in colder climates should be heated both for worker comfort and to prevent freezing of facility equipment and piping. The heating system may consist of a combination of perimeter convectors to offset building transmission losses, underfloor slab or infrared radiation for comfort, and makeup air units for ventilation. Where natural gas is available and local codes allow, direct-fired gas heaters can be an economical compromise to provide a high degree

of worker comfort. Air curtains or door heaters are not needed in shop where doors are opened infrequently.

Enclosed Servicing Areas. Although most locomotive servicing is done outside, some railroads use enclosed servicing areas for protection from weather and extreme cold. Servicing operations include refilling fuel tanks, replenishing sand (used to aid traction), draining toilet holding tanks, checking lubrication oil and radiator coolant levels, and performing minor repairs. Generally, a locomotive spends less than 1 h in the servicing area. Ventilation is needed to reduce personnel exposure to exhaust gas contaminants and remove heat emitted from engine radiators. The designer should also consider the presence of vapors from fuel oil dispensing and silica dust from sanding. Heating may also be included in the design depending on the need for worker comfort and the operations performed.

Ventilation for servicing areas should be similar to that for maintenance and repair areas. Where possible, hoods should be used in lieu of dilution ventilation. However, coordinating hood locations with engine exhaust points may be difficult because different types of locomotives may be coupled together in consists. Elevated sanding towers and distribution piping may also interfere. Contaminant levels might be higher in servicing areas than in the shops because of constantly idling locomotives and occasional higher-speed movements in servicing areas. For dilution ventilation, the designer should ascertain the type of operations planned for the facility and make a volumetric analysis of expected rates of contaminant generation and air exchange.

Infrared radiation should be considered for heating. As with maintenance and repair areas, direct-fired gas heaters may be economical. Door heaters or air curtains may be justified because of frequent opening of doors or a lack of doors.

Overbuilds. With increasing real estate costs, the space above trackways and station platforms is commonly built over to enclose the locomotive operation area. Ventilation is needed in overbuilds to reduce crew and passenger exposure to exhaust gases and to remove heat emitted from engine radiators and vehicle air-conditioning systems. Overbuilds are generally not heated.

Exhaust emissions from a diesel passenger locomotive operating in an overbuild are higher than from an idling locomotive because of head-end power requirements. The designer should determine the types of locomotives to be used and the operating practices in the overbuild. As with locomotive repair shops and servicing areas, hoods are recommended to capture engine exhaust. According to the *Overbuild of Amtrak Right-of-Way Design Policy* (Amtrak 2005), the air temperature at the exhaust source will be between 350 and 950°F. A typical ventilation design could have hoods approximately 18 to 23 ft above the top of the rail, with throat velocities between 30 and 36.7 fps. For dilution ventilation, the designer should perform a volumetric analysis of contaminant generation and air exchange rates.

Contaminant Level Criteria

In most locations, diesel exhaust is not regulated specifically, although concentrations of many substances found in diesel exhaust are regulated. The U.S. Occupational Safety and Health Administration (OSHA 2001a, 2001b) identifies carbon dioxide (CO_2), carbon monoxide (CO), nitrogen dioxide (NO_2), nitric oxide (NO), diesel particulate matter (DPM), and sulfur dioxide (SO_2) as major components of diesel exhaust. Thirty-one additional substances are identified as minor components, with seventeen of these being polycyclic aromatic hydrocarbons (PAH). These minor components are elements of DPM.

Federal OSHA requirements establish limits for these compounds in the United States, although a few states may set more restrictive requirements. Also, the American Council of Governmental and Industrial Hygienists (ACGIH) publishes guideline values for use in industrial hygiene that are not legally enforceable, but

Table 11 Contaminant Exposure Limits for NO₂

(For information only—check updated local regulations)

Entity	NO₂, ppm(v)			NO₂, mg/m³		
	8 h	15 min	Ceiling	8 h	15 min	Ceiling
OSHA – USA (PEL)			5			9
ACGIH – USA (TLV)	3	5		6	9	
NIOSH – USA (REL)		1			2	
Australia	3	5		6	9	
Belgium	3	5		6	9	
Denmark	3	5		6	9	
Finland	3	6		6	11	
France		3			6	
Germany			5			9
Japan						
Sweden	1*			2*		
Switzerland	3	6		6	11	
United Kingdom	3	5		6	9	
China			2.6			5

*Limit specifically for NO₂ from exhaust fumes.

may evolve more quickly than OSHA requirements (ACGIH 2001). Other countries set their own contaminant limits, though these may draw heavily from the ACGIH and other U.S. publications.

When no regulations exist for DPM, nitrogen dioxide (NO_2) is present in diesel exhaust emissions at the highest levels relative to its published limits. In these circumstances, systems designed to control nitrogen dioxide will maintain other exhaust-related contaminants well below their respective limits. Table 11 shows published exposure limits in parts per million (ppm). Federal OSHA, ACGIH, and NIOSH limits are current as of at least February 2003. Other limits are taken primarily from an international database of participating countries (ILO 2003; Lu 1993). Contaminant limits are often expressed in mg/m³, even in regions where I-P units are used.

Most authorities do not currently distinguish DPM from other particulates; however, this may change. The ACGIH recently added DPM measured as elemental carbon to its TLVs (ACGIH 2003). A 0.1 mg/m³ limit for elemental carbon in diesel environments has been established in Germany (MSHA 2001a, 2001b). Recent laws enacted by the Mine Safety and Health Administration are targeted toward limiting DPM in mining environments (MSHA 2001a, 2001b). These changes may foreshadow action by OSHA. In this changing environment, designers must check local regulations in the time and place of construction for applicable limits.

Contaminant Emission Rate

Locomotive contaminant emissions have been measured primarily for environmental reasons, and data for some models have been published in the environmental literature (Table 12). These data are classified for different duty-cycles of operation and different throttle settings, and were obtained from controlled tests conducted under steady-state operation. Engine speed, engine power, fuel rate, and engine airflow are typically reported. Emissions are usually reported for carbon monoxide (CO), oxides of nitrogen (NO_x), hydrocarbons, sulfur dioxide (SO_2), and particulates. Manufacturers can provide this information for specific engine models, and should be consulted for current and specific data for design projects.

Note that passenger locomotives consume a greater amount of power when idling with head-end power (HEP) to serve passenger related needs. A passenger train idle at HEP can produce five times the amount of NO_x emissions as the same train idling with no HEP effects (Fritz 1994). Thus, this is an important distinction between passenger railway stations, where HEP is likely to be required, and repair facilities, where HEP is not likely to be needed.

Available emissions data have been targeted toward outdoor pollution concerns, which imposes some limitations in applying it to indoor settings. Only recent tests document exhaust temperatures, a

quantity useful to design engineers concerned with sprinkler systems. Emissions data come from steady-state tests on engines whose operation has been allowed to stabilize for an hour or more, so a safety factor is suggested to allow for higher emissions related to cold start and transient operation. Also, the data include only a combined NO_x emissions value. Field measurements in locomotive facilities found that about 13% (by mass) of ambient NO_x could be attributed to NO_2 (Musser and Tan 2004). This factor can be used estimate NO_2 source emissions from available data. The applicability of these data to design applications is supported by comparisons of CFD models based on published emissions data and field measurements taken in repair shops that showed reasonable agreement between the measured and predicted values (Musser and Tan 2004).

Locomotive Operation

Designers need to anticipate locomotive operation during the design phase, particularly when estimating source strength based on published locomotive emissions data. Some important parameters include the number of operating locomotives, and the location, duration, and throttle position at which they operate. The number of locomotives likely to be operating can be estimated based on shop or station schedules. Although it is important to remember that a locomotive could idle at any location inside a facility, there are often practical cues to identify the most common or likely locations. These include platforms, facility layout, location of equipment for servicing toilets, fuel stations, or other service equipment. In small shops, the layout may create one or two convenient positions in which locomotives are very likely to be parked.

Other operating parameters may be more difficult to estimate, particularly in shops. Field observations for ASHRAE Research Project RP-1191 recorded locomotive operation in several shops varying from a few minutes to an hour in duration, usually at idle and low throttle settings (Musser and Tan 2004). Operation was influenced by shop rules, practices, and conventions, which are valuable to consider during the design phase. The cooperation and involvement of shop employees in the design stage can help integrate these practices so that the design conforms to the needs of the facility, rather than the other way around.

Design Methods

General Exhaust Systems. A contaminant-based procedure using a simplified equation developed with computational fluid dynamics can be used to design general exhaust systems using the steps below. The simplified equation was developed to flexibly adapt to changes in contaminant limits. Figures 20 and 21 show schematic drawings of such a system.

Step 1: Verify that design parameters to be used in the simplified equation fall within the ranges for which the equation is valid.

- Ceiling height Z must be 20 to 45 ft.
- Fan spacing X must be 20 to 60 ft.
- Exhaust fan flow Q must provide 5 to 12 air changes per hour (ach)

Step 2: Verify that other facility characteristics show reasonable agreement with the assumptions of the parametric study:

- Fan dimensions L: Exhaust fan or duct dimensions are 5 by 5 ft.
- Fan placement: Exhaust fans or duct openings are centered above each track.
- Locomotive exhaust temperature T: 350°F.
- Locomotive exhaust flow rate F: 2000 cfm.
- Radiator fans: For many locomotive models, radiator fans do not operate when the locomotive is idling, and no radiator fan flow was modeled in this study. If radiator fans will be operating, they may alter the indoor airflow patterns.

Table 12   Sample Diesel Locomotive Engine Emission Data[a]

Throttle Position (Notch)	Engine Speed, rpm	Engine Power, bhp	Engine Airflow,[b] cfm	Fuel Rate, lb/h	NO$_x$, lb/h	CO, lb/h	HC, lb/h	SO$_2$, lb/h	Particulates, lb/h
Four-Stroke Cycle, With Head End Power (HEP)
8, Freight	1050	3268	8816	1103	81	5.9	3.9	0.51	0.96
7, HEP	900	2771	7068	929	71	13	3.0	0.43	1.1
6, HEP	900	2254	5668	762	62	11	2.6	0.35	0.92
5, HEP	900	1777	4433	609	51	10	1.6	0.28	0.64
4, HEP	900	1023	2677	369	34	3.2	1.2	0.17	0.51
3, HEP	900	713	2055	266	22	2.3	0.94	0.12	0.49
2, HEP	900	431	1656	174	14	1.6	0.88	0.08	0.54
1, HEP	900	322	1651	144	13	1.6	0.92	0.07	0.65
HEP idle	900	185	1511	81	6.3	2.0	1.1	0.04	0.91
Standby	720	512	1441	189	16	1.9	0.81	0.09	0.65
High idle	450	34	466	23	1.9	0.49	0.40	0.01	0.13
Low idle	370	22	NA[c]	17	1.1	0.70	0.35	0.01	0.10
Two-Stroke Cycle, No Head End Power (HEP)
8	903	3210	8880	1060	86	8.1	2.0	0.49	1.5
7	821	2540	7100	833	56	4.1	1.2	0.38	0.97
6	726	1700	5310	572	38	1.5	0.85	0.26	0.64
5	647	1390	4630	480	33	1.4	0.79	0.22	0.58
4	563	1060	3950	368	28	0.61	0.64	0.17	0.42
3	489	714	3410	254	24	0.42	0.51	0.12	0.30
2	337	370	2200	142	13	0.46	0.33	0.07	0.12
1	337	207	2270	91	7.7	0.34	0.25	0.04	0.07
High idle	339	14	2390	32	2.5	0.17	0.21	0.02	0.05
Low idle	201	10	1320	14	1.3	0.08	0.08	0.01	0.02
Auxiliary Engine/Alternator for Head End Power (HEP)
NA[c]	1800	699	1930	275	17	7.3	0.69	0.13	0.37
NA[c]	1800	566	2190	226	17	1.1	0.78	0.10	NA[c]
NA[c]	1800	438	2010	179	13	0.53	0.67	0.08	0.26
NA[c]	1800	377	1900	157	10	0.39	0.61	0.07	0.25
NA[c]	1800	305	1810	135	8.4	0.39	0.56	0.06	0.23
NA[c]	1800	238	1710	114	6.5	0.40	0.57	0.05	0.20
NA[c]	1800	173	1640	95	4.8	0.41	0.55	0.04	0.18
NA[c]	1800	31	1480	55	2.2	0.46	0.60	0.03	0.16

[a]Data from Southwest Research Institute (SwRI 1992).   [b]Intake, corrected to standard air density 0.0751 lb/ft^3.   [c]Data not available.
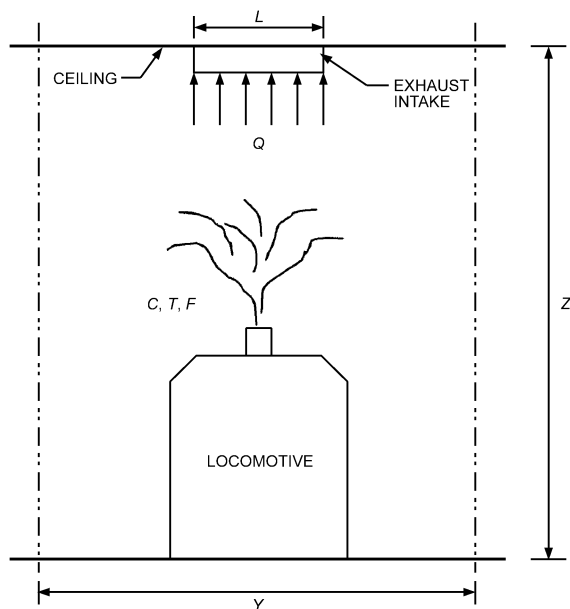
Fig. 20   Section View of Locomotive and General Exhaust System
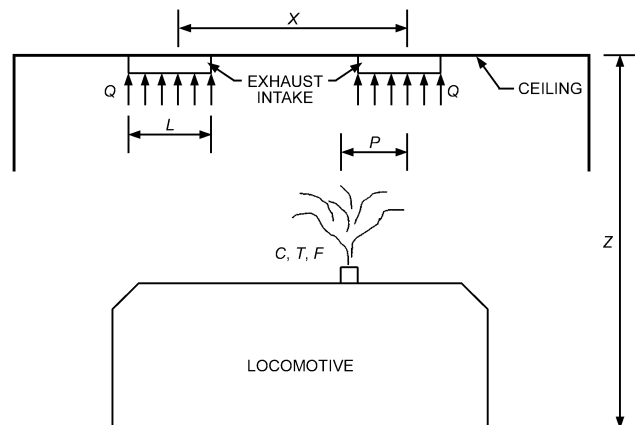
Fig. 21   Elevation View of Locomotive and General Exhaust System

- Operating time: The equation is based on steady state conditions, so it is not necessary to assume a maximum operating time.
- Concurrent operation: The equation allows for concurrent operation on different tracks. However, it does not include concurrent operation of more than one locomotive on the same track.
- Track-to-track spacing Y: 25 ft.

- Ambient temperature: 90°F. This was selected because warmer ambient temperatures tend to reduce the upward buoyancy of warm exhaust gases.

Step 3: Obtain emissions data for critical contaminants and determine the design indoor concentration limit for the critical contaminant.

- Emissions data for some locomotive models are published in the environmental literature, and data for specific locomotives can be obtained from the manufacturer. The emissions rate for a given locomotive model depends on throttle position and whether head-end power is used.
- Acceptable indoor concentration limits can be determined from legal requirements at the location and time of construction. The designer may also wish to consider recommended limits from organizations such as ACGIH. To allow a margin of safety, a designer might choose a contaminant limit that is lower than the published legal limit.

Contaminant limits are often expressed in mg/m^3, even in regions where I-P units are used. A contaminant limit in ppm(v) can be converted to mg/m^3 for use in the simplified equation as follows (ASHRAE *Standard* 62.1):

$$\text{ppm(v)} \times \frac{\text{Molecular weight}}{24.45} = mg/m^3 \qquad (19)$$

Step 4: Select a fan flow rate and calculate the maximum concentration to which occupants would be exposed using Equation (20). Table 13 gives values for constants a to j whether occupants will be standing on the floor or a 4 ft high platform.

$$C_{occ} = 10^{-3} C_{emissions}(a + bQ + cP + dX + eZ + \qquad (20)$$
$$fQZ + gPX + hPZ + iXZ + jPXZ)$$

where

C_{occ} = maximum time-averaged concentration of critical contaminant to which occupants could be exposed, mg/m^3

$C_{emissions}$ = concentration of critical contaminant in exhaust emissions, mg/m^3

a to j = constants found in Table 13

Q = total exhaust fan flow rate required, ach; must be between 5 and 12 ach

Z = ceiling height; must be 20 to 45 ft

X = fan spacing; must be 20 to 60 ft

P = locomotive offset position, dimensionless; $P = 0$ under fan and $P = 1$ between fans. Other values for P can be calculated based on the distance of the locomotive stack from the nearest exhaust fan d and the fan spacing X:

$$P = 2\frac{d}{X} \qquad (21)$$

Table 13 Constants for Equation (20)

Constant	No Platform	With 4 ft Platform
a	20.0	22.5
b	−0.551	−0.773
c	−3.32	−2.09
d	−0.106	−0.109
e	−0.308	−0.346
f	0.0119	0.0159
g	0.235	0.236
h	0.0792	0.0407
i	0.00191	0.00190
j	−0.00505	−0.00499

Step 5: Compare C_{occ} obtained in step 4 with the concentration limit C_{limit} determined in Step 3. If $C_{occ} < C_{limit}$, the selected flow rate is adequate. If $C_{occ} > C_{limit}$, repeat step 4 with a higher flow rate until a concentration less than the limit is obtained.

Step 6: Verify that the result is between 5 and 12 ach.

- If the flow rate obtained is between 5 and 12 ach, this is the system size.
- If the flow rate obtained is less than 5 ach, the designer could
  - Design for 5 ach.
  - Perform a more detailed analysis to verify that less than 5 ach will provide acceptable contaminant control. For rates less than the 1.5 cfm/ft^2 recommended by ASHRAE *Standard* 62.1 or in the case of unusual sources, the presence of contaminants other than those from diesel exhaust in the space (e.g., liquid fuel) should also be considered.
- If the flow rate obtained is greater than 12 ach, the designer could
  - Adjust the other parameters to attempt to reduce the air change requirement.
  - Perform a more detailed analysis to verify the necessary air flow requirement.

Example 2. Perform design calculations for a passenger locomotive repair shop.

Step 1: Verify design parameters. The planned facility ceiling height is 30 ft, which falls within the 20 to 45 ft range for which the simplified equation is valid. The planned fan spacing is 50 ft, which also falls within the required range of 20 to 60 ft.

Step 2: Verify other facility characteristics.

- Exhaust fans: Exhaust openings with an area of approximately 25 ft^2 will be used, and fans will be centered above each track.
- Locomotive: Operating locomotives are usually high idle or lower. When moving in, they will not exceed throttle position 1. Information obtained from the manufacturer of the locomotive most commonly serviced in this facility indicates an exhaust flow rate of 2300 cfm, an exhaust temperature of 375°F, and NO_x generation of 7.661 lb/h. Radiator fans will not operate in the high idle position for this locomotive.
- Track-to-track spacing is 27 ft. Locomotives may operate concurrently on adjacent tracks, but concurrent operation on the same track is not planned.
- These characteristics are reasonably similar to the assumptions upon which the simplified equation is based.

Step 3: Obtain emissions data and determine the design limit.

- The critical contaminant for this design is nitrogen dioxide (NO_2). Emission data from the manufacturer state that the NO_x generation rate is 7.661 lb/h. Field measurements conducted for ASHRAE Research Project RP-1191 (Musser and Tan 2004) showed that ambient NO_2 concentrations were about 13% of ambient NO_x levels. Therefore, the NO_2 generation rate is estimated to be 13% of the total, or 0.996 lb/h, which converts to 452 g/h. For an exhaust flow rate of 2300 cfm, the concentration of NO_2 in the exhaust is 116 mg/m^3.

$$C_{emissions} = \left(\frac{452 \text{ g/h}}{2300 \text{ ft}^3/\text{min}}\right)\left(\frac{1}{60 \text{ min/h}}\right)$$
$$\left(\frac{1}{0.02832 \text{ m}^3/\text{ft}^3}\right)(1000 \text{ mg/g}) = 116 \text{ mg/m}^3$$

- OSHA currently requires a 5 ppm(v) ceiling for NO_2, but NIOSH and other sources recommend a 1 ppm(v) 15 min short-term exposure limit (STEL). The designer decides to select the lower 1 ppm(v) limit, and to design for 0.5 ppm(v) (i.e., 0.94 mg/m^3) to allow for a safety factor for variations in emissions or operation.

$$\frac{0.5 \text{ ppm(v)} \times 46}{24.45} = 0.94 \text{ mg/m}^3$$

Step 4: Select a flow rate and solve for the contaminant concentration. Ceiling height is 30 ft, and fan spacing 50 ft. Based on the placement of services in the shop, expect that the stack of an operating locomotive will be at most 12.5 ft from the nearest exhaust fan, so $P = 0.5$. The shop does have a 4 ft high platform where workers may stand, so Equation (20) is solved using a platform. First, try fans that provide 5 ach:

$$C_{occ} = 10^{-3}(116 \text{ mg/m}^3)(22.5 - 0.773Q + 2.09P - 0.109X -$$
$$0.346Z + 0.0159QZ + 0.236PX - 0.0407PZ +$$
$$0.00190XZ + 0.00499PXZ) = 0.97 \text{ mg/m}^3$$

- Iterate between steps 5 and 4. With 5 ach, $C_{occ} = 0.97$ mg/m³. This is greater than the desired limit of 0.94 mg/m³. If the fan flow rate is increased to provide 6.5 ach, C_{occ} decreases to 0.935 mg/m³. This meets the design criterion.

Step 5: Verify that the fan flow rate is between 5 and 12 ach. No further analysis is needed.

Exhaust Hood Design. A similar equation was also developed for design of exhaust hood systems. However, results from the parametric set of computational fluid dynamics simulations performed to develop the equation were shown to be highly specific to the situation and geometry shown in Figures 22 and 23. Therefore, these equations should not be used unless the given assumptions are exactly matched. For further information on hood design, see ACGIH (1998).

Step 1: Verify that the design parameters to be used in the simplified equation fall within the ranges for which it is valid.

- Hood mounting height H must be 3 to 8 ft.
- Hood length L must be 5 to 11 ft.
- Exhaust fan flow Q must provide 5 to 12 ach.

Step 2: Verify that other facility characteristics agree with the assumptions of the parametric study. These assumptions are:

- Hood width W: 5 ft.
- Hood placement: Hoods are centered above each track at 60 ft intervals.
- Hood operation: All hoods switched on together.
- Ceiling height Z: 25 ft.
- Locomotive exhaust temperature T: 350°F.
- Locomotive exhaust flow rate F: 2000 cfm.
- Radiator fans: Radiator fans do not operate.
- Operating time: The results of the study are based on steady-state conditions, so it is not necessary to assume a maximum operating time.
- Concurrent operation: The study allows for concurrent operation on different tracks. However, it does not include concurrent operation of more than one locomotive on the same track.
- Track-to-track spacing Y: 25 ft.
- Ambient temperature: 90°F.

Step 3: Obtain emissions data for critical contaminants and determine the design indoor concentration limit for the critical contaminant. This can be done using the procedure described for general exhaust systems.

Step 4: Select a fan flow rate and calculate the maximum concentration to which occupants would be exposed using Equation (22). Table 14 gives values for constants a to l for occupants standing on the floor or on a 4 ft high platform.
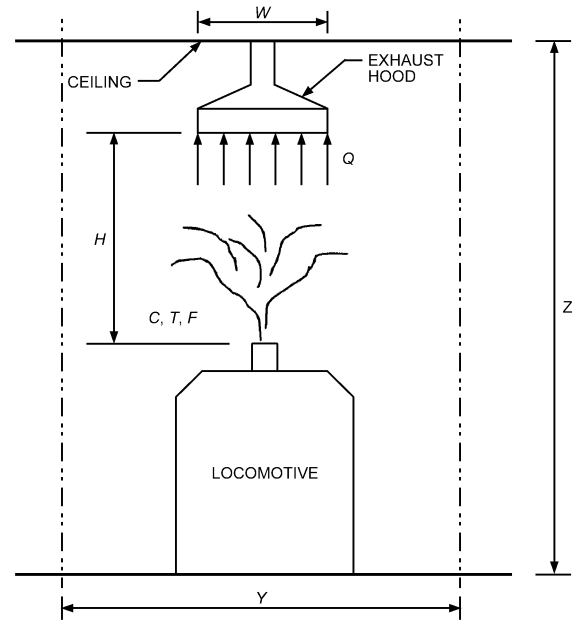
Fig. 22   Section View of Locomotive and Exhaust Hood System
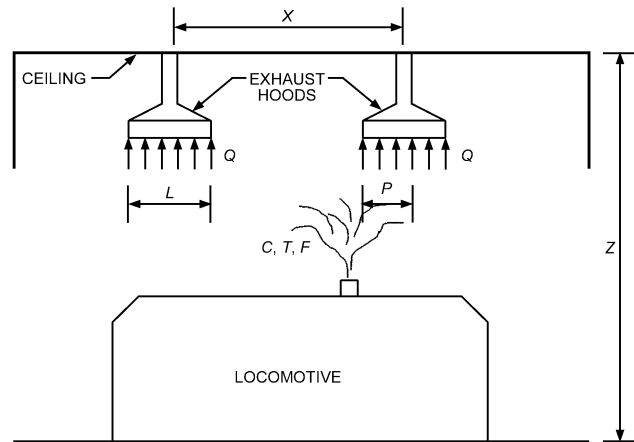
Fig. 23   Elevation View of Locomotive and Exhaust Hood System

$$C_{occ} = 10^{-3}C_{emissions}(a + bQ + cP + dH + eL + fQP +$$
$$gQH + hQL + iPH + jHL + kQPH + lQHL) \qquad (22)$$

where

C_{occ} = maximum time-averaged concentration of critical contaminant to which occupants could be exposed, mg/m³

$C_{emissions}$ = concentration of critical contaminant in exhaust emissions, mg/m³

a to l = constants in Table 14

Q = total exhaust fan flow rate required, ach; must be 5 to 12 ach

H = hood mounting height; must be 3 to 8 ft

L = fan spacing; must be 5 to 11 ft

P = locomotive offset position; dimensionless; $P = 0$ centered under hood and $P = 1$ under edge of hood. Other values for P can be calculated based on distance d of locomotive stack from center of nearest exhaust hood and hood length L:

$$P = \frac{2d}{L} \qquad (23)$$

Table 14 Constants for Equation 22

Constant	No Platform	With 4 ft Platform
a	0.717	2.19
b	−0.160	−0.401
c	0.900	2.18
d	−0.168	−0.283
e	−0.0508	−0.275
f	−0.129	−0.332
g	0.0381	0.0684
h	0.0245	0.0846
i	−0.174	−0.351
j	0.0294	0.0575
k	0.0290	0.0560
l	−0.00588	−0.0134

Step 5: Compare C_{occ} obtained in step 4 with the concentration limit C_{limit} determined in step 3. If $C_{occ} < C_{limit}$, the selected flow rate is adequate. If $C_{occ} > C_{limit}$, repeat step 4 with a higher flow rate until a concentration less then the limit is obtained.

Step 6: Verify that the result is between 5 and 12 ach.

- If the flow rate obtained is between 5 and 12 ach, this is the system size.
- If the flow rate obtained is less than 5 ach, the designer could
  - Design for 5 ach.
  - Perform a more detailed analysis to verify that less than 5 ach will provide acceptable contaminant control. For rates less than the 1.5 cfm/ft^2 recommended by ASHRAE *Standard* 62.1 or in the case of unusual sources, the presence of contaminants other than those from diesel exhaust in the space should also be considered (e.g., liquid fuel).
- If the flow rate obtained is greater than 12 ach, the designer could
  - Adjust the other parameters to attempt to reduce the air change requirement.
  - Perform a more detailed analysis to verify the necessary air flow requirement.

EQUIPMENT

The ability of an enclosed vehicular facility to function depends mostly on the effectiveness and reliability of its ventilation system, which must operate effectively under the most adverse environmental, climatic, and vehicle traffic conditions. A tunnel ventilation system should also have more than one dependable power source, to prevent interruption of service.

Fans

Fan manufacturers should be prequalified and should be responsible under one contract for furnishing and installing the fans, bearings, drives (including any variable-speed components), motors, vibration devices, sound attenuators, discharge/inlet dampers, and limit switches. Other ventilation-related equipment, such as ductwork, may be provided under a subcontract.

The prime concerns in selecting the type, size, and number of fans include the total theoretical ventilation airflow capacity required and a reasonable comfort margin. Fan selection is also influenced by how reserve ventilation capacity is provided either when a fan is inoperative, or during maintenance or repair of either the equipment or the power supply.

Selection (i.e., number and size) of fans needed to meet normal, emergency, and reserve ventilation capacity requirements of the system is based on the principle of parallel fan operation. Actual airflow capacities can be determined by plotting fan performance and system curves on the same pressure-volume diagram.

Fans selected for parallel operation should operate in a particular region of their performance curves, so that airflow capacity is not
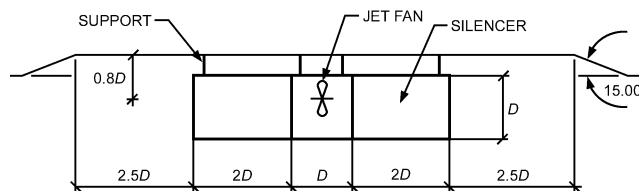
Fig. 24 Typical Jet Fan Arrangement in Niche

transferred back and forth between fans. This is done by selecting a fan size and speed such that the duty point, no matter how many fans are operating, falls well below the unstable performance range. Fans operating in parallel should be of equal size and have identical performance curves. If airflow is regulated by speed control, all fans should operate at the same speed. If airflow is regulated by dampers or by inlet vane controls, all dampers or inlet vanes should be set at the same angle. For axial-flow fans, blades on all fans should be set at the same pitch or stagger angle.

Jet fans can be used for longitudinal ventilation to provide a positive means of smoke and air temperature management in tunnels. This concept was proven as part of the Memorial Tunnel Fire Ventilation Test Program (MHD/FHWA 1995). Although jet fans deliver relatively small air quantities at high velocity, the momentum produced is transferred to the entire tunnel, inducing airflow in the desired direction. Jet fans are normally rated in terms of thrust rather than airflow and pressure, and can be either unidirectional or reversible.

Number and Size of Fans. The number and size of fans should be selected by comparing several fan arrangements based on the feasibility, efficiency, and overall economy of the arrangement, and the duty required. Factors that should be studied include (1) annual power cost for operation, (2) annual capital cost of equipment (usually capitalized over an assumed equipment life of 30 years for mass transit tunnel fans, or 50 years for highway and railroad tunnel fans), and (3) annual capital cost of the structure required to house the equipment (usually capitalized over an arbitrary structure life of 50 years).

Two views are widely held regarding the proper number and size of fans: the first advocates a few high-capacity fans, and the second prefers numerous low-capacity fans. In most cases, a compromise arrangement produces the greatest efficiency. The number and size of the fans should be selected to build sufficient flexibility into the system to meet the varying ventilation demands created by daily and seasonal traffic fluctuations and emergency conditions.

Jet fan sizing is usually limited by space available for installation in the tunnel. Typically mounted on the tunnel ceiling (above the vehicle traffic lanes), or on the tunnel walls (outside the vehicle traffic lanes), jet fans are sometimes placed in niches to minimize the height or width of the entire tunnel boundary. However, niches must be adequately sized to avoid reducing the thrust of the fans. A typical jet fan niche arrangement is provided in Figure 24.

For longitudinal ventilation using jet fans, the required number of fans is defined (once fan size and tunnel airflow requirements have been determined) by the total thrust required to overcome the tunnel resistance (pressure loss), divided by the individual jet fan thrust, which is a function of the mean air velocity in the tunnel. Jet fans installed longitudinally should be at least 100 fan diameters apart so that the jet velocity does not affect the performance of downstream fans. Jet fans installed side by side should be at least two fan diameters (centerline to centerline) apart.

Type of Fan. Normally, ventilating an enclosed vehicular facility requires a large volume of air at relatively low pressure. Some fans have low efficiencies under these conditions, so the choice of a suitable fan type is often limited to a centrifugal, vaneaxial or jet fan.

Special Considerations. Special attention must be given to a fan installed where **airflow and pressure transients** are caused by vehicle passage. If the transient tends to increase airflow through the fan (i.e., positive flow in front of the vehicle toward an exhaust fan, or negative flow behind the vehicle toward a supply fan), blade loading must not become high enough to produce long-term fatigue failures. If the disturbance tends to decrease airflow through the fan (i.e., negative flow behind the vehicle toward an exhaust fan, or positive flow in front of the vehicle toward a supply fan), the fan performance characteristic must have adequate comfort margins to prevent an aerodynamic stall.

The ability to **rapidly reverse** the rotation of a tunnel ventilation fan is important during an emergency. This requirement must be considered in selection and design of the fan and drive system.

Fan Design and Operation. Fans and fan components (e.g., blade-positioning mechanisms, drives, bearings, motors, controls, etc.) that must operate in the exhaust airstream during a fire or smoke emergency should be capable of operating at maximum speed under the temperatures specified by the following standards or calculation procedures:

- NFPA *Standard* 130 for mass transit and passenger rail tunnels
- NFPA *Standard* 502 for road tunnels
- Computer simulations or other calculations for the maximum expected temperatures, in railroad tunnels and other enclosed vehicular facilities

Fans and dampers that are operated infrequently or for emergency service only should be activated and tested at least once every three months to ensure that all rotating elements are in good condition and properly lubricated. The period of activity should be long enough to achieve stabilized temperatures in fan bearings and motor windings. Fans with multispeed motors should be operated at all speeds.

Inlet boxes can be used to protect centrifugal fan bearings and drives from high temperatures, corrosive gases, and particulate matter in exhaust air during emergency operating mode. This arrangement requires special attention to fan shaft design, because of overhung drive loads (see the section on Fan Shafts).

Reversible axial flow fans should be able to be rapidly reversed from the maximum design speed in one direction to the maximum design speed in the opposite direction in less than 60 s. Fan design should include the effects of temperature changes associated with reversing airflow direction. All components of reversible fans should be designed for a minimum of four reversal cycles per year for 50 years without damage.

Housings for variable-pitch axial flow fans should be furnished with instruments to measure airflow in both directions. Capped connections should be provided for measuring the pressure developed across the fan. The fan should also be protected from operating in a stall region.

To minimize blade failure in axial flow fans, the following precautions should be taken:

- Blades should be secured to the hub by positive locking devices.
- The fan inlet (and discharge, if reversible) should be protected against entry of foreign objects that could damage the rotating assembly.
- The natural frequency (static and rotating) of the blade and the maximum stress on the blade surface (for all operating points on the fan characteristic curve) should be measured during factory testing.
- For mass transit and rail systems, fans subjected to airflow and air pressure reversals caused by train passage should be designed (and tested, for verification) to withstand 4,000,000 cycles of airflow reversals.

When a fan includes a variable-frequency drive (VFD), factory testing with a production version of the VFD should be done to ensure adequate operation and compatibility with the fan system.

Jet fan blades should be strong enough to withstand the air temperatures created by a fire. Design calculations for jet fans should consider that the fire might destroy the fan(s) at the fire location, and that the jet fans downstream of the fire will operate under high temperatures.

Fan Shafts. Fan shafts should be designed so that the maximum deflection of assembled fan components, including forces associated with the fan drive, does not exceed 0.005 in. per foot of shaft length between centers of the bearings. For centrifugal fans where the shaft overhangs the bearing, the maximum deflection at the centerline of the fan drive pulley should not exceed 0.005 in. per foot of shaft length between the center of the bearing and the center of the fan drive pulley.

Good practice suggests that the fundamental bending mode frequency of the assembled shaft, wheel, or rotor be more than 50% higher than the highest fan speed. The first resonant speed of all rotational components should be at least 125% above the maximum speed. The fan assembly should be designed to withstand, for at least 3 min, all stresses and loads from an overspeed test at 110% of maximum design fan speed.

Bearings. Fan and motor bearings should have a minimum equivalent L10 rated life of 10,000 h, as defined by the American Bearing Manufacturers Association. Special attention must be given to belt-driven fans, because improper tensioning or overtensioning of belts can drastically reduce the bearing life, belt life, and possibly shaft life.

For **axial-flow fans** and **jet fans**, each fan motor bearing and fan bearing should have a monitoring system that senses individual bearing vibrations and temperatures, and provides a warning alarm if either rises above the manufacturer-specified range.

Because of their low speed (generally less than 450 rpm), **centrifugal fans** are not always provided with bearing vibration sensors, but they do require temperature sensors with warning alarm and automatic fan shutdown. Bearing pedestals for centrifugal fans should provide rigid support for the bearings with negligible impediments to airflow. Static and dynamic loading of the shaft and the impeller, and the maximum force from tension in the belts, should be considered.

Corrosion-Resistant Materials. Choosing a particular material or coating to protect a ventilation fan from corrosive gas is a matter of economics. Selection of the material and/or coating should be based on the installation environment, fan duty, and an expected service life of 50 years.

Sound. For ventilation fan sound attenuator design, construction documents should specify the following:

- Speed and direction of airflow, and number of operating fans
- Maximum dBA rating or NC curve(s) acceptable under installed conditions, and locations of fan supply inlet and exhaust outlet where these requirements apply
- OSHA or local requirements for jet-fan-generated noise limits, which may require silencers of 1 to 2 fan diameters in length
- That the dBA rating at certain locations, such as intake louvers, discharge louvers, or discharge stacks, may not exceed OSHA or local requirements
- That the fan manufacturer must furnish and install the acoustical treatment needed to bring the level down to an acceptable value if measured sound values exceed the specified maximum
- NFPA-recommended maximum noise levels for emergency fan operations

Dampers

Dampers play a major role in overall tunnel safety and the successful operation of a tunnel ventilation system. Dampers regulate airflow into and out of the tunnel, through either natural or forced ventilation, to maintain acceptable temperatures. Dampers also relieve pressure: opening and closing dampers allows tunnel air to

be driven out of ventilation shafts located in front of moving vehicles, and for fresh air to be drawn into tunnels by ventilation shafts located behind moving vehicles. Dampers are also used with fans to dilute or remove carbon monoxide (CO), flammable gases, or other toxic fumes from tunnels. However, the most important function of dampers is to direct ventilation air and smoke flow during a fire emergency. In this function, fans and dampers operate in conjunction to exhaust smoke and control its flow in the tunnel in support of passenger evacuations and firefighter ingress.

Damper Design. Tunnel ventilation damper design requires a thorough understanding of design criteria, installation methods, environmental surroundings, equipment life expectancy, maintenance requirements, and operating system. Damper construction varies, but the general construction is based on the following design criteria:

- Maximum fan operating pressure
- Normal and rogue tunnel air pressures
- Maximum air temperature
- Maximum air velocity
- Corrosion protection
- Maintainability and life expectancy of the equipment
- Maximum damper module size
- Maximum air leakage

Fan Pressure. The maximum operating pressure that the damper will withstand during normal or emergency ventilation operations is typically the maximum pressure that the fan can generate at shutoff. This air pressure is generally 4 to 50 in. of water.

Normal and Rogue Tunnel Pressures. Some dampers in the track area of a train tunnel see much higher positive and negative pressure pulses than the maximum pressure generated by the fan. These high-pressure pulses are caused by the piston action of trains moving through the tunnel. A closed damper is subjected to positive pressures as trains approach, and to negative pressures as trains pass. This pressure reversal subjects damper blades and related components to reverse bending loads that must be considered to prevent premature fatigue failures. The magnitude of the pulsating pressure depends on factors such as maximum train speed, tunnel length, clearance between the train and tunnel walls, and amount of air pushed through the dampers.

Pulsating pressure is part of normal tunnel operation. However, a rogue train condition (e.g., if a train operates at high speed during an emergency, or if there is a runaway train) could occur once or twice during the lifetime of a tunnel ventilation system. Dampers must be designed for both day-to-day fatigue and for maximum train-speed conditions.

Design specifications should require that the damper and its components meet reverse bending load criteria for from 1 to 6 million reverse bending cycles for normal, day-to-day train operations. This number equates to a train passing a damper once every 5 to 20 min for 30 to 50 years. The number of cycles can be adjusted for each application. In addition, the specifying engineer should indicate the pressure that could result from a (once or twice in a lifetime) rogue train condition.

Typically, actuators for tunnel dampers must be selected to operate against the maximum fan pressure. Because reversing pressures only occur briefly, and because normal train operations cease during an emergency, actuators are not expected to operate under either reverse pressure or rogue train conditions.

Temperature. The maximum temperature can vary for each tunnel project; some specifying engineers use the temperature limits recommended by NFPA. Typical equipment specifications state that dampers, actuators, and accessories should meet the operational requirements of the emergency ventilation fan system described in NFPA *Standard* 130: "Emergency ventilation fans, their motors, and all related components exposed to the exhaust airflow shall be

designed to operate in an ambient atmosphere of 482°F for a minimum of 1 h with actual values to be determined by design analysis. In no case shall the operating temperatures be less than 300°F."

Some tunnel design engineers have specified higher air temperature criteria based on additional design considerations. A few road tunnels have been designed for the possibility of two tanker trucks carrying flammable liquids exploding from an accident in the tunnel, which would subject tunnel dampers to very high temperatures. Dampers for projects of this type, or others projects with special considerations, have been designed for maximum temperatures up to 800°F. The specifying engineer must evaluate design conditions for each project and determine what the maximum temperature could be.

Dampers, and especially damper actuators, must be specially constructed to operate reliably in high-temperature conditions for extended periods. It is important to verify that the proposed equipment can provide this required safety function. Because standard testing procedures have not been developed, a custom high-temperature test of a sample damper and actuator should be considered for inclusion in the equipment specifications.

Air Velocity. The maximum air velocity for a tunnel damper design is determined from the maximum airflow expected through the damper during any operating condition. Maximum airflow could be generated from more than one fan, depending on the system design. Actuators for tunnel dampers are typically selected to operate against the maximum airflow that dampers will be exposed to in a worst-case scenario. Thus, the maximum airflow must be specified. It is important that the engineer understands the effect of damper free area on expected airflow and pressure loss. Air velocity through a damper can vary significantly depending on damper construction and the installation configuration used.

A multiple-panel damper assembly usually has less free area than a single panel damper because of the additional blockage caused by its vertical and/or horizontal mullions. A multiple-panel damper assembly with 60 to 70% free area can have two to four times the pressure loss of a single-panel damper with 80% free area. Therefore, airflow through the multiple-panel damper assembly can be significantly lower than that through a comparable single-panel damper.

The configuration of the damper installation can also affect free area, airflow, and pressure loss. For example, a damper can either be mounted to the face of an opening, or in the opening itself. The damper mounted in the opening has a smaller free area because of the additional blockage of the damper frame, resulting in lower airflow and higher pressure loss. Damper performance also depends on where the damper is mounted (e.g., in a chamber, at one or the other end of a duct). AMCA *Standard* 500-D has more information on damper mounting configurations.

Corrosion Protection. Construction materials for tunnel projects vary considerably; their selection is usually determined based on one or more of the following reasons:

- Initial project cost
- Environmental conditions
- Life expectancy of the equipment
- Success or failure of previous materials used on similar projects
- Engineer's knowledge of and/or experience with the materials required to provide corrosion protection
- Design criteria (e.g., tunnel air pressure, temperature, and velocity)

The corrosion resistance of a damper should be determined by the environment in which it will operate. A damper installation near a saltwater or heavy industrial area may need superior corrosion protection compared to one in a rural, nonindustrialized city. Underground or indoor dampers may need less corrosion protection. However, many underground dampers are also exposed to rain, snow,

and sleet. These and other factors must be evaluated by the engineer before a proper specification can be written.

Tunnel dampers have been made from commercial-quality galvanized steel, hot-dipped galvanized steel, anodized aluminum, aluminum with a duranodic finish, carbon steel with various finishes, and stainless steel, including types 304, 304L, 316, 316L, and 317.

Maintainability and Life Expectancy of Equipment. These issues are of great concern when specifying dampers that may be difficult to access regularly for servicing, inspection, or maintenance. In addition, the equipment may be difficult to replace, should it fail prematurely because it was marginally designed for the pressures, temperatures, corrosion resistance, etc., required for the application.

Thus, some specifying engineers purposely design dampers with a more robust construction. Dampers may be specified with heavier and/or more corrosion-resistant materials than may be required for the application, in hopes of reducing operational problems and maintenance costs and extending the life expectancy of the product. Typical methods used to design dampers of more robust construction include the following:

- Limiting blade, frame, and linkage deflections to a maximum of $L/360$
- Selecting actuators for 200 to 300% of the actual damper torque required
- Using large safety factors for stresses and deflections of high stress components
- Specifying heavier material sizes and gages than necessary
- Using more corrosion-resistant materials and finishes than required
- Using slower damper activation times (from full-close to full-open, and vice versa)

Many damper specifications include a quality assurance (QA) or system assurance program (SAP) to ensure that required performance levels are met. Others include an experience criterion that requires damper manufacturers to have five installations with five or more years of operating experience; a list of projects and contact names must be submitted so the current customer can communicate with past customers regarding the product performance. These requirements help ensure that reliable products are supplied.

Module Size. The maximum damper module size is one of the most important initial-cost factors. Many dampers can be made as a single-module assembly, or in several sections that can be field-assembled into a single-module damper. However, some damper openings are very large and it may not be practical to manufacture the damper in a one-piece frame construction because of shipping, handling, and/or installation problems.

Generally, initial cost is lower with fewer modules because they have fewer blades, frames, jackshafts, actuators, and mullion supports. However, other factors, such as job site access, lifting capabilities, and installation labor costs, must also be included in the initial-cost analysis. These factors vary for each project, so the specifying engineer must evaluate each application separately.

Air Leakage. The specifying engineer must consider air leakage through the damper when evaluating a design. Leakage is usually specified in terms of cubic feet per minute per square foot of damper face area, at a specific air pressure. As differential air pressure increases across the damper, so does air leakage. Leakage is, therefore, a function of air pressure and damper crack area, rather than of airflow. To reduce leakage, the number or size of or leakage paths must be reduced. The most common method is adding damper blades and/or jamb seals, which can reduce leakage to an acceptable value.

Some specifications note the allowable damper air leakage as a percentage of the normal or maximum airflow. However, it is important to recognize that this is only an acceptable practice if the airflow and associated pressure are known.

Damper Applications and Types. Dampers allow or restrict airflow into a tunnel, and balance airflow in a tunnel. **Fan isolation dampers** can be installed in multiple-fan systems to (1) isolate any parallel, nonoperating fan from those operating, to prevent short-circuiting and airflow/pressure losses through the inoperative fan, (2) prevent serious windmilling of an inoperative fan, (3) provide a safe environment for maintenance and repair work on each fan. Single-fan installations may also have a fan isolation damper to prevent serious windmilling from natural or piston-effect drafts and facilitate fan maintenance.

Ventilation dampers control the amount of fresh air supplied to and exhausted from the tunnel and station areas. They may also serve as **smoke exhaust dampers** (SEDs), **bypass dampers** (BDs), **volume dampers** (VDs) and **fire dampers** (FDs), depending on their location and design. Two types of ventilation dampers are generally used: (1) trapdoor, which is installed in a vertical duct, such that the door lies horizontal when closed; and, (2) multiblade louver with parallel-operating blades. Both types can be driven by either an electric or pneumatic actuator; the fan controller operates the damper actuator. During normal operation, the damper usually closes when the fan is shut off and opens when the fan is turned on.

The trapdoor damper is simple and works satisfactorily where a vertical duct enters a plenum fan room through an opening in the floor. This damper is usually constructed of steel plate, with welded angle iron reinforcements; it is hinged on one side and closed by gravity against the embedded angle frame of the opening. The opening mechanism is usually a shaft sprocket-and-chain device. The drive motor and gear drive mechanism, or actuator, must develop sufficient force to open the damper door against the maximum (static) air pressure differential that the fan can develop. This pressure can be obtained from the fan performance curves. Limit switches start and stop the gear-motor drive or actuator at the proper position.

Fan isolation and ventilation dampers in places other than vertical ducts should have multiblade louvers. These dampers usually consist of a rugged channel frame, the flanges of which are bolted to the flanges of the fan, duct, wall, or floor opening. Damper blades are assembled with shafts that turn the bearings mounted on the outside of the channel frame. This arrangement requires access outside the duct for bearing and shaft lubrication, maintenance, and linkage operation space. Multiblade dampers should have blade edge and/or end seals to meet air leakage requirements for the application.

The trapdoor damper, properly fabricated, is inherently a low-leakage design because of its weight and the overlap at its edges. Multiblade dampers can also have low air leakage, but they must be carefully constructed to ensure tightness on closing. The pressure drop across a fully opened damper and the air leakage rate across a fully closed damper should be verified by the appropriate test procedure in AMCA *Standard* 500-D. A damper that leaks excessively under pressure can cause the fan to rotate counter to its power rotation, thus making restarting dangerous and possibly damaging to the fan motor drive.

Actuators and Accessory Selections. Tunnel damper specifications typically call for dampers, actuators, and accessories to meet the operational requirements of **emergency ventilation fans**, as described by NFPA *Standard* 130. Damper actuators are normally specified to be electric or pneumatic. Actuator selection is determined by the engineer or the customer and is usually decided by available power or initial and/or long-term operating cost.

Pneumatic Actuators. Pneumatic actuators are available in many sizes and designs; rack and pinion, air cylinder, and Scotch yoke are common configurations. Each can be of either double-action (i.e., air is supplied to operate the damper in both directions) or spring-return construction. A spring-return design uses air to power it in one direction, and a spring to drive it in the opposite direction; it is selected when it is desirable to have the damper fail to a set position on loss of air supply. Many manufacturers make pneumatic

actuators; several manufacturers make both double-acting and spring-return designs capable of operating at 482°F for 1 h.

Electric Actuators. Electric actuators are also available in a variety of designs and sizes. They can be powered in both directions to open and close the damper; in this case the actuator usually fails in its last position on loss of power. Electric actuators that are powered in one direction and spring-driven in the opposite direction are also available. As with pneumatic actuators, spring return is selected when it is desirable to have the damper fail to a particular position on loss of power. There are fewer manufacturers of electric actuators than pneumatic actuators, and most do not make a spring-return design, especially in larger-torque models. Also, very few electric actuators are capable of operating at 482°F for 1 h, particularly for spring-return designs.

Actuator Selection. Actuators for tunnel dampers are typically sized to operate against the maximum airflow or velocity and pressure that will occur in a worst-case scenario. The maximum air velocity corresponds to the maximum airflow expected through the damper during any of its operating conditions. In addition, the maximum airflow could come from more than one fan, depending on system design. The maximum pressure on the damper during normal or emergency ventilation is typically the maximum pressure that the fan can generate at shutoff.

Actuators are sized and selected to (1) overcome the frictional resistance of blade bearings, linkage pivots, jackshafting assemblies, etc.; and (2) compress the blade and jamb seals to meet specified air leakage requirements. Therefore, the specifying engineer must determine maximum airflow (or air velocity) and pressure conditions, and maximum air leakage criteria.

Safety factors in actuator selection are not always addressed in tunnel damper specifications. This omission can result in operational problems if a manufacturer selects actuators too close to the required operating torque. Tunnel dampers are expected to function for many years when properly maintained. Also, damper manufacturers determine their torque requirements based on square, plumb, and true installations. These factors, plus the fact that dirt and debris build-up can increase damper torque, suggest that a minimum safety factor of at least 50% should be specified. Greater safety factors can be specified for some applications; however, larger actuators require larger drive shafts with higher initial cost.

Supply Air Intake. Supply air intakes require careful design to ensure that air drawn into the ventilation system is of the best quality available. Factors such as recirculation of exhaust air or intake of contaminants from nearby sources should be considered. Louvers or grilles are usually installed over air intakes for aesthetic, security, or safety reasons. Bird screens are also necessary if the openings between louver blades or grilles are large enough to allow birds to enter.

Because of the large volumes of air required in some ventilation systems, it may not be possible for intake louvers to have face air velocities low enough to be weatherproof. Therefore, intake plenums, ventilation shafts, fan rooms, and fan housings often need water drains. Windblown snow can also enter the fan room or plenum, but snow accumulation usually does not prevent the ventilation system from operating satisfactorily, if additional floor drains are located near the louvers.

Sound attenuation devices may be needed in fresh air intakes or exhaust outlets to keep fan-generated noise from disturbing the outside environment. If noise reduction is required, the total system (i.e., fans, housings, plenums, ventilation building, and location and size of air intakes and exhaust outlets), should be investigated. Fan selection should be based on the total system, including pressure drop from sound attenuation devices.

Exhaust Outlets. Exhaust air from ventilation systems should be discharged above street level and away from areas with human occupancy. Contaminant concentrations in exhaust air should not be a concern if the system is working effectively. However, odors and entrained particulate matter in exhaust make discharge into occupied areas undesirable. Exhaust stack discharge velocity, usually a minimum of 2000 fpm, should be high enough to disperse contaminants into the atmosphere.

Evasé (flared) outlets have been used to regain some static pressure and thereby reduce exhaust fan energy consumption. Unless the fan discharge velocity is over 2000 fpm, the energy savings may not offset the cost of the evasé.

In a vertical or near-vertical exhaust fan discharge connection to an exhaust duct or shaft, rainwater will run down the inside of the stack into the fan. This water will dissolve material deposited from vehicle exhaust on the inner surface of the stack and become extremely corrosive. Therefore, fan housings should be corrosion-resistant or specially coated to protect the metal.

Discharge louvers and gratings should be sized and located so that their discharge is not objectionable to pedestrians or contaminating to nearby air intakes. Airflow resistance across the louver or grating should also be minimized. Discharge air velocities through sidewalk gratings are usually limited to 500 fpm. Bird screens should be provided if the exhaust airstream is not continuous (i.e., 24 h/day, 7 days/week), and the openings between louver blades are large enough to allow birds to enter.

Corrosion resistance of the louver or grating should be determined by the corrosiveness of the exhaust air and the installation environment. Pressure drop across the louvers should be verified by the design engineer using the appropriate test procedure in AMCA *Standard* 500-L (1999).

NATIONAL AND INTERNATIONAL SAFETY STANDARDS AND GUIDELINES

National Fire Protection Association (NFPA)

NFPA developed fire protection standards for both road tunnels and for rapid transit facilities. The standard for transit systems is known as NFPA *Standard* 130, and the standard for road tunnels is NFPA *Standard* 502, Standard for Road Tunnels, Bridges and other Limited Access Highways.

In addition to the NFPA *Standards* 130 and 502, NFPA publishes many standards and codes that are applicable to enclosed vehicular facilities, including the following:

- Standard for Portable Fire Extinguishers, NFPA 10, 2002
- Standard for the Installation of Sprinkler Systems, NFPA 13, 2002
- Standard for the Installation of Standpipe and Hose Systems, NFPA 14, 2003
- Standard for the Installation of Stationary Pumps for Fire Protection, NFPA 20, 2003
- Standard for Water Tanks for Private Fire Protection, NFPA 22, 2003
- Flammable and Combustible Liquids Code, NFPA 30, 2003
- Code for Motor Fuel Dispensing Facilities and Repair Garages, NFPA 30A, 2003
- Standard for Spray Application using Flammable or Combustible Materials, NFPA 33, 2000
- Standard for Gaseous Hydrogen Systems at Consumer Sites, NFPA 50A, 1999
- Compressed Natural Gas (CNG) Vehicular Fuel Systems Code, NFPA 52, 1998
- Liquefied Natural Gas (LNG) Vehicular Fuel Systems Code, NFPA 57, 1999
- Liquefied Petroleum Gas Code, NFPA 58, 1998
- National Electrical Code®, NFPA 70, 2005
- Recommended Practice for Electrical Equipment Maintenance, NFPA 70B, 2002
- National Fire Alarm Code®, NFPA 72®, 2002
- Standard for Fire Doors and Fire Windows, NFPA 80, 1999

- Standard for Parking Structures, NFPA 88A, 1998
- Standard for Repair Garages, NFPA 88B, 1997
- Life Safety Code®, NFPA 101®, 2003
- Standard for Emergency and Standby Power Systems, NFPA 110, 2002
- Standard on Stored Electrical Energy Emergency and Standby Power Systems, NFPA 111, 2001
- Standard for Safeguarding Construction, Alteration, and Demolition Operations, NFPA 241, 2004
- Standard for Fire Protection in Wastewater Treatment and Collection Facilities, NFPA 820, 2003
- Standard on Emergency Services Incident Management System, NFPA 1561, 2002
- Standard for Fire Hose Connections, NFPA 1963, 2003

PIARC

PIARC, or The World Road Association (formerly the Permanent International Association of Road Congresses), has for many years published technical reports on tunnels and tunnel ventilation in conjunction with their quadrennial World Road Congresses. The PIARC Technical Committee on Road Tunnel Operation (C3.3) and its working groups have published several important specific documents on tunnel ventilation and fire safety:

- Classification of Tunnels, Existing Guidelines and Experiences, 05.03.B, 1995
- Road Safety in Tunnels, 05.04.B, 1995
- Fire and Smoke Control in Road Tunnels, 05.05.B, 1999
- Systems and Equipment for Fire and Smoke Control in Road Tunnels, 05.16.B, 2007
- Good Practice for the Operation and Maintenance of Road Tunnels, 05.13.B, 2005
- Road Tunnels: Vehicle Emissions and Air Demand for Ventilation, 05.14.B, 2004
- Traffic Incident Management Systems Used in Road Tunnels, 05.15.B, 2004
- Cross Section Geometry in Uni-directional Tunnels, 05.11.B, 2002
- Cross Section Design of Bidirectional Road Tunnels, 05.12.B, 2004

Country-Specific Standards and Guidelines

Many countries publish tunnel guidelines and standards primarily for use in their country; however, many of these documents do provide an insight into numerous unique tunnel applications. A partial list of those available is as follows:

- Design Guidelines Tunnel Ventilation, RVS 9.261 & RVS 9.262, Transportation and Road Research Association, National Roads Administration, Austria, 1997
- Regulations on Technical Standards and Conditions for Design and Construction of Tunnels on Roads, Croatia, 1991
- Design of Road Tunnels, *Standard* CSN 73 7507, Czech Republic
- Road Tunnel Equipment, *Guideline* TP 98, Czech Republic
- Inter-Ministerial *Circular* 2000-63: Safety in the Tunnels of the National Highways Network, Ministry of the Establishment, Transport and Housing, France, 2000
- Guidelines for Equipment and Operation of Road Tunnels, Road and Transportation Research Association (RABT), Federal Ministry of Traffic, Germany, 2006
- Safety of Traffic in Road Tunnels with Particular Reference to Vehicles Transporting Dangerous Materials, Italy, 1999
- National Safety Standard of Emergency Facilities in Road Tunnels, Japan Road Association, Japan, 2001
- Recommendations for the Ventilation of Road Tunnels Public Works and Water Management (RWS), the Netherlands, 2005
- *Norwegian Design Guide—Road Tunnels*, Public Roads Administration, Directorate of Public Roads, Norway, 1992

- Ventilation of Road Tunnels, Sub-Committee 61, Nordisk Vejteknisk Forbund (NVF), *Report* 6, 1993
- *Manual for the Design, Construction and Operation of Tunnels*, IOS-98, Spain, 1998
- *Tunnel 2004—General Technical Specification for New Tunnels and Upgrading of Old Tunnels*, Swedish National Road Association, Sweden, 2004
- *Ventilation for Road Tunnels*, Swiss Federal Roads Authority (FEDRO), 2004
- *Design of Road Tunnels*, the Highways Agency, United Kingdom, 1999
- Road Tunnel Design Guidelines, Federal Highway Administration, FHWA-IF-05-023, United States, 2004

Building Codes

Often, building codes have supplementary information and requirements applicable to a specific type of facility. For example, the ventilation of a vehicle parking garage is also governed by the applicable building code. Some of the commonly used codes are as follows:

- The **International Building Code (IBC)** with its own subset of mechanical codes such as the International Plumbing Code (IPC) and the International Mechanical Code (IMC).
- **National building codes** were the Uniform Building Code (UBC), Building Officials Code Association (BOCA), and the Southern Building Code Conference (SBCC), each of which was applicable in different parts of the country but now have been replaced by the IBC. The designer should be aware that some states and municipalities have not yet adopted the IBC and hence are still governed by the last version of the UBC, BOCA, or SBCC, as applicable.
- Most states have their own **state building codes** with specific modifications to the IBC or other as applicable for the conditions specific to the state, such as seismic requirements.
- Many cities and municipalities have their own **local building codes**. The designer should be aware of the local code governing the facility. Many cities have adopted specific NFPA standards into their codes, thereby giving them the freedom to write amendments to these standards. The design of the facility is required to conform to the requirements of the amended standard, unless a specific waiver is applied for and obtained.

Ancillary areas of tunnels such as electrical and mechanical equipment rooms, which are often adjacent to the tunnel they serve, are governed by the applicable building codes. For the separation requirements between these ancillary spaces and the tunnel, the more stringent of the requirements between the building code and the applicable NFPA Standard will apply. The authority having jurisdiction should always be consulted when there is any doubt in the application of this separation requirement.

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NFPA. 2005. National electrical code®. *Standard* 70. National Fire Protection Association, Quincy, MA.

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NFPA. 2007. Standard for fixed guideway transit and passenger rail systems. *Standard* 130. National Fire Protection Association, Quincy, MA.

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CHAPTER 14

LABORATORIES

MODERN laboratories require regulated temperature, humidity, relative static pressure, air motion, air cleanliness, sound, and exhaust. This chapter addresses biological, chemical, animal, and physical laboratories. Within these generic categories, some laboratories have unique requirements. This chapter provides an overview of the HVAC characteristics and design criteria for laboratories, including a brief overview of architectural and utility concerns. This chapter does not cover pilot plants, which are essentially small manufacturing units.

The function of a laboratory is important in determining the appropriate HVAC system selection and design. Air-handling, hydronic, control, life safety, and heating and cooling systems must function as a unit and not as independent systems. HVAC systems must conform to applicable safety and environmental regulations.

Providing a safe environment for all personnel is a primary objective in the design of HVAC systems for laboratories. A vast amount of information is available, and HVAC engineers must study the subject thoroughly to understand all the factors that relate to proper and optimum design. This chapter serves only as an introduction to the topic of laboratory HVAC design. HVAC systems must integrate with architectural planning and design, electrical systems, structural systems, other utility systems, and the functional requirements of the laboratory. The HVAC engineer, then, is a member of a team that includes other facility designers, users, industrial hygienists, safety officers, operators, and maintenance staff. Decisions or recommendations by the HVAC engineer may significantly affect construction, operation, and maintenance costs.

Laboratories frequently use 100% outside air, which broadens the range of conditions to which the systems must respond. They seldom operate at maximum design conditions, so the HVAC engineer must pay particular attention to partial load operations that are continually changing due to variations in internal space loads, exhaust requirements, external conditions, and day-night variances. Most laboratories will be modified at some time. Consequently, the HVAC engineer must consider to what extent laboratory systems should be adaptable for other needs. Both economics and integration of the systems with the rest of the facility must be considered.

LABORATORY TYPES

Laboratories can be divided into the following general types:

- **Biological laboratories** are those that contain biologically active materials or involve the chemical manipulation of these materials. This includes laboratories that support such disciplines as biochemistry, microbiology, cell biology, biotechnology, immunology, botany, pharmacology, and toxicology. Both chemical fume hoods and biological safety cabinets are commonly installed in biological laboratories.
- **Chemical laboratories** support both organic and inorganic synthesis and analytical functions. They may also include laboratories in the material and electronic sciences. Chemical laboratories commonly contain a number of fume hoods.
- **Animal laboratories** are areas for manipulation, surgical modification, and pharmacological observation of laboratory animals. They also include animal holding rooms, which are similar to laboratories in many of the performance requirements but have an additional subset of requirements.
- **Physical laboratories** are spaces associated with physics; they commonly incorporate lasers, optics, nuclear material, high- and low-temperature material, electronics, and analytical instruments.

Laboratory Resource Materials

The following are general or specific resource materials applicable to various types of laboratories.

- ACGIH. 2001. *Industrial Ventilation: A Manual of Recommended Practice*, 24th ed. American Conference of Governmental Industrial Hygienists, Cincinnati, OH.
- AIA. 2001 ed. Guidelines for Design and Construction of Hospital and Health Care Facilities. American Institute of Architects, Washington, D.C.
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- BOCA. Building, Mechanical, and Fire Prevention Model Codes. Building Officials and Code Administrators International, Country Club Hills, IL.
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Other regulations and guidelines may apply to laboratory design. All applicable institutional, local, state, and federal requirements should be identified before design begins.

[Editor's note: see issuing organizations for latest editions of publications listed in this section.]

HAZARD ASSESSMENT

Laboratory operations potentially involve some hazard; nearly all laboratories contain some type of hazardous materials. The owner's designated safety officers should perform a comprehensive hazard assessment, which must be completed before the laboratory can be designed. These safety officers include, but are not limited to, the chemical hygiene officer, radiation safety officer, biological safety officer, and fire and loss prevention official. The hazard assessment should be incorporated into the chemical hygiene plan, radiation safety plan, and biological safety protocols.

Hazard study methods such as hazard and operability analysis (HAZOP) can be used to evaluate design concepts and certify that the HVAC design conforms to the applicable safety plans. The nature and quantity of the contaminant, types of operations, and degree of hazard dictate the types of containment and local exhaust devices. For functional convenience, operations posing less hazard potential are conducted in devices that use directional airflow for personnel protection (e.g., laboratory fume hoods and biological safety cabinets). However, these devices do not provide absolute containment. Operations having a significant hazard potential are conducted in devices that provide greater protection but are more restrictive (e.g., sealed glove boxes).

The design team should visit similar laboratories to assess successful design approaches and safe operating practices. Each laboratory is somewhat different. Its design must be evaluated using appropriate, current standards and practices rather than duplicating existing and possibly outmoded facilities.

DESIGN PARAMETERS

The following design parameters must be established for a laboratory space:

- Temperature and humidity, both indoor and outdoor
- Air quality from both process and safety perspectives, including the need for air filtration and special treatment (e.g., charcoal, HEPA, or other filtration of supply or exhaust air)
- Equipment and process heat gains, both sensible and latent
- Minimum ventilation rates
- Equipment and process exhaust quantities
- Exhaust and air intake locations
- Style of the exhaust device, capture velocities, and usage factors
- Need for standby equipment and emergency power
- Alarm requirements.
- Potential changes in the size and number of fume hoods
- Anticipated increases in internal loads
- Room pressurization requirements

It is important to (1) review design parameters with the safety officers and scientific staff, (2) determine limits that should not be exceeded, and (3) establish the desirable operating conditions. For areas requiring variable temperature or humidity, these parameters must be carefully reviewed with the users to establish a clear understanding of expected operating conditions and system performance.

Because laboratory HVAC systems often incorporate 100% outside air systems, the selection of design parameters has a substantial effect on capacity, first cost, and operating costs. The selection of proper and prudent design conditions is very important.

Internal Thermal Considerations

In addition to the heat gain from people and lighting, laboratories frequently have significant sensible and latent loads from equipment and processes. Often, data for equipment used in laboratories are unavailable or the equipment has been custom built. Data on heat release from animals that may be housed in the space can be found in Chapter 10 of the 2005 *ASHRAE Handbook—Fundamentals* and in Alereza and Breen (1984).

Careful review of the equipment to be used, a detailed understanding of how the laboratory will be used, and prudent judgment are required to obtain good estimates of the heat gains in a laboratory. The convective portion of heat released from equipment located within exhaust devices can be discounted. Heat from equipment that is directly vented or heat from water-cooled equipment should not be considered part of the heat released to the room. Any unconditioned makeup air that is not directly captured by an exhaust device must be included in the load calculation for the room. In many cases, additional equipment will be obtained by the time a laboratory facility has been designed and constructed. The design should allow for this additional equipment.

Internal load as measured in watts per square foot is the average continuous internal thermal load discharged into the space. It is not a tabulation of the connected electrical load because it is rare for all equipment to operate simultaneously, and most devices operate with a duty cycle that keeps the average electrical draw below the nameplate information. When tabulating the internal sensible heat load in a laboratory, the duty cycle of the equipment should be obtained from the manufacturer. This information, combined with the nameplate data for the item, may provide a more accurate assessment of the average thermal load.

The HVAC system engineer should evaluate equipment nameplate ratings, applicable use and usage factors, and overall diversity. Much laboratory equipment includes computers, automation, sample changing, or robotics; this can result in high levels of use even during unoccupied periods. The HVAC engineer must evaluate internal heat loads under all anticipated laboratory-operating modes. Because of highly variable equipment heat gain, individual laboratories should have dedicated temperature controls.

Two cases encountered frequently are (1) building programs based on generic laboratory modules and (2) laboratory spaces that are to be highly flexible and adaptive. Both situations require the design team to establish heat gain on an area basis. The values for area-based heat gain vary substantially for different types of laboratories. Heat gains of 5 to 25 W/ft^2 or more are common for laboratories with high concentrations of equipment.

Architectural Considerations

Integrating utility systems into the architectural planning, design, and detailing is essential to providing successful research facilities. The architect and the HVAC system engineer must seek an early understanding of each other's requirements and develop integrated solutions. HVAC systems may fail to perform properly if the architectural requirements are not addressed correctly. Quality assurance of the installation is just as important as proper specifications. The following play key roles in the design of research facilities:

Modular Planning. Most laboratory programming and planning is based on developing a module that becomes the base building block for the floor plan. Laboratory planning modules are frequently 10 to 12 ft wide and 20 to 30 ft deep. The laboratory modules may be developed as single work areas or combined to form multiple-station work areas. Utility systems should be arranged to reflect the architectural planning module, with services provided for each module or pair of modules, as appropriate.

Development of Laboratory Units. National Fire Protection Association (NFPA) *Standard* 45 requires that laboratory units be designated. Similarly, the International, Uniform, and Building Officials and Code Administrators International (BOCA) model codes require the development of control areas. Laboratory units or control areas should be developed, and the appropriate hazard levels should be determined early in the design process. The HVAC designer should review the requirements for maintaining separations between laboratories and note requirements for exhaust ductwork to serve only a single laboratory unit.

Additionally, NFPA *Standard* 45 requires that no fire dampers be installed in laboratory exhaust ductwork. Building codes offer no relief from maintaining required floor-to-floor fire separations. These criteria and the proposed solutions should be reviewed early in the design process with the appropriate building code officials. The combination of the two requirements commonly necessitates the construction of dedicated fire-rated shafts from each occupied floor to the penthouse or building roof.

Provisions for Adaptability and Flexibility. Research objectives frequently require changes in laboratory operations and programs. Thus, laboratories must be flexible and adaptable, able to accommodate these changes without significant modifications to the infrastructure. For example, the utility system design can be flexible enough to supply ample cooling to support the addition of heat-producing analytical equipment without requiring modifications to the HVAC system. Adaptable designs should allow programmatic research changes that require modifications to the laboratory's infrastructure within the limits of the individual laboratory area and/or interstitial and utility corridors. For example, an adaptable design would allow the addition of a fume hood without requiring work outside that laboratory space. The degree of flexibility and adaptability for which the laboratory HVAC system is designed should be determined from discussion with the researchers, laboratory programmer, and laboratory planner. The HVAC designer should have a clear understanding of these requirements and their financial impact.

Early Understanding of Utility Space Requirements. The amount and location of utility space are significantly more important in the design of research facilities than in that of most other buildings. The available ceiling space and the frequency of vertical distribution shafts are interdependent and can significantly affect the architectural planning. The HVAC designer must establish these parameters early, and the design must reflect these constraints. The designer should review alternative utility distribution schemes, weighing their advantages and disadvantages.

High-Quality Envelope Integrity. Laboratories that have stringent requirements for the control of temperature, humidity, relative static pressure, and background particle count generally require architectural features to allow the HVAC systems to perform properly. The building envelope may need to be designed to handle relatively high levels of humidification and slightly negative building pressure without moisture condensation in the winter or excessive infiltration. Some of the architectural features that the HVAC designer should evaluate include

- Vapor barriers—position, location, and kind
- Insulation—location, thermal resistance, and kind
- Window frames and glazing
- Caulking
- Internal partitions—their integrity in relation to air pressure, vapor barriers, and insulation value
- Finishes—vapor permeability and potential to release particles into the space
- Doors
- Air locks

Air Intakes and Exhaust Locations. Mechanical equipment rooms and their air intakes and exhaust stacks must be located to avoid intake of fumes into the building. As with other buildings, air intake locations must be chosen to minimize fumes from loading docks, cooling tower discharge, vehicular traffic, etc.

LABORATORY EXHAUST AND CONTAINMENT DEVICES

FUME HOODS

The Scientific Equipment and Furniture Association (SEFA 1996) defines a laboratory fume hood as "a ventilated enclosed work space intended to capture, contain, and exhaust fumes, vapors, and particulate matter generated inside the enclosure. It consists basically of side, back and top enclosure panels, a floor or counter top, an access opening called the face, a sash(es), and an exhaust plenum equipped with a baffle system for airflow distribution. Figure 1 shows the basic elements of a general-purpose benchtop fume hood.

Fume hoods may be equipped with a variety of accessories, including internal lights, service outlets, sinks, air bypass openings, airfoil entry devices, flow alarms, special linings, ventilated base storage units, and exhaust filters. Under counter cabinets for storage of flammable materials require special attention to ensure safe installation. NFPA *Standard* 30, Flammable and Combustible Liquids Code, does not recommend venting these cabinets; however, ventilation is often required to avoid accumulation of toxic or hazardous vapors. Ventilation of these cabinets by a separately ducted supply and exhaust that will maintain the temperature rise of the cabinet interior within the limits defined by NFPA *Standard* 30 should be considered.

Types of Fume Hoods

The following are the primary types of fume hoods and their applications:

Standard (approximately constant-volume airflow with variable face velocity). Hood that meets basic SEFA definition. Sash may be vertical, horizontal, or combination.

Application: Research laboratories—frequent or continuous use. Moderate to highly hazardous processes; varying procedures.

Bypass (approximately constant-volume airflow with approximately constant face velocity). Standard vertical sash hood modified with openings above and below the sash. The openings are sized to minimize the change in the face velocity, which is generally to 3 or 4 times the full-open velocity, as the sash is lowered.

Application: Research laboratories—frequent or continuous use. Moderate to highly hazardous processes; varying procedures.
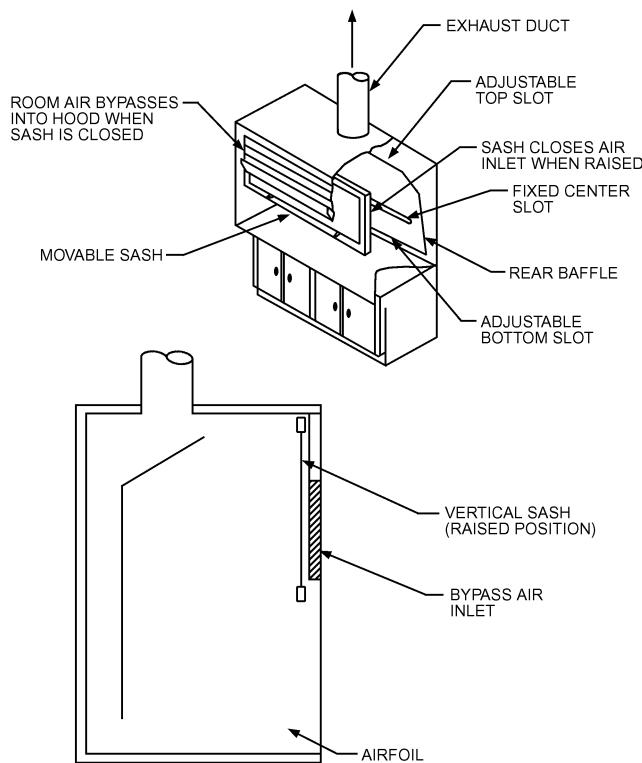
Fig. 1   Bypass Fume Hood with Vertical Sash and Bypass Air Inlet

Variable Volume (constant face velocity). Hood has an opening or bypass designed to provide a prescribed minimum air intake when the sash is closed and an exhaust system designed to vary airflow in accordance with sash opening. Sash may be vertical, horizontal, or a combination of both.

Application: Research laboratories—frequent or continuous use. Moderate to highly hazardous processes; varying procedures.

Auxiliary Air (approximately constant-volume airflow with approximately constant face velocity). A plenum above the face receives air from a secondary air supply that provides partially conditioned or unconditioned outside air.

Application: Research laboratories—frequent or continuous use. Moderate to highly hazardous processes; varying procedures.

Note: Many organizations restrict the use of this type of hood.

Process (approximately constant-volume airflow with approximately constant face velocity). Standard hood without a sash. By some definitions, this is not a fume hood. Considered a ventilated enclosure.

Application: Process laboratories—intermittent use. Low-hazard processes; known procedures.

Radioisotope. Standard hood with special integral work surface, linings impermeable to radioactive materials, and structure strong enough to support lead shielding bricks. The interior must be constructed to prevent radioactive material buildup and allow complete cleaning. The ductwork should have flanged neoprene gasketed joints with quick disconnect fasteners that can be readily dismantled for decontamination. High-efficiency particulate air (HEPA) and/or charcoal filters may be needed in the exhaust duct.

Application: Process and research laboratories using radioactive isotopes.

Perchloric Acid. Standard hood with special integral work surfaces, coved corners, and non-organic lining materials. Perchloric acid is an extremely active oxidizing agent. Its vapors can form unstable deposits in the ductwork that present a potential explosion hazard. To alleviate this hazard, the exhaust system must be equipped with an internal water washdown and drainage system, and the ductwork must be constructed of smooth, impervious, cleanable materials that are resistant to acid attack. The internal washdown system must completely flush the ductwork, exhaust fan, discharge stack, and fume hood inner surfaces. The ductwork should be kept as short as possible with minimum elbows. Perchloric acid exhaust systems with longer duct runs may need a zoned washdown system to avoid water flow rates in excess of the capacity to drain the water from the hood. Because perchloric acid is an extremely active oxidizing agent, organic materials should not be used in the exhaust system in places such as joints and gaskets. Ducts should be constructed of a stainless steel material, with a chromium and nickel content not less than that of 316 stainless steel, or of a suitable nonmetallic material. Joints should be welded and ground smooth. A perchloric acid exhaust system should only be used for work involving perchloric acid.

Application: Process and research laboratories using perchloric acid. Mandatory use because of explosion hazard.

California. Special hood with sash openings on multiple sides (usually horizontal).

Application: For enclosing large and complex research apparatus that require access from two or more sides.

Walk-In. Standard hood with sash openings to the floor. Sash can be either horizontal or vertical.

Application: For enclosing large or complex research apparatus. Not designed for personnel to enter while operations are in progress.

Distillation. Standard fume hood with extra depth and 1/3- to 1/2-height benches.

Application: Research laboratory. For enclosing tall distillation apparatus.

Canopy. Open hood with an overhead capture structure.

Application: Not a true fume hood. Useful for heat or water vapor removal from some work areas. Not to be substituted for a fume hood. Not recommended when workers must bend over the source of heat or water vapor.

Fume Hood Sash Configurations

The work opening has operable glass sash(es) for observation and shielding. A sash may be vertically operable, horizontally operable, or a combination of both. A vertically operable sash can incorporate single or multiple vertical panels. A horizontally operable sash incorporates multiple panels that slide in multiple tracks, allowing the open area to be positioned across the face of the hood. The combination of a horizontally operable sash mounted within a single vertically operable sash section allows the entire hood face to be opened for setup. Then the opening area can be limited by closing the vertical panel, with only the horizontally sliding sash sections used during experimentation. Either multiple vertical sash sections or the combination sash arrangement allow the use of larger fume hoods with limited opening areas, resulting in reduced exhaust airflow requirements. Fume hoods with vertically rising sash sections should include provisions around the sash to prevent the bypass of ceiling plenum air into the fume hood.

Fume Hood Performance

Containment of hazards in a fume hood is based on the principle that a flow of air entering at the face of the fume hood, passing

through the enclosure, and exiting at the exhaust port prevents the escape of airborne contaminants from the hood into the room.

The following variables affect the performance of the fume hood:

- Face velocity
- Size of face opening
- Sash position
- Shape and configuration of entrance
- Shape of any intermediate posts
- Inside dimensions and location of work area relative to face area
- Location of service fittings inside the fume hood
- Size and number of exhaust ports
- Back baffle and exhaust plenum arrangement
- Bypass arrangement, if applicable.
- Auxiliary air supply, if applicable
- Arrangement and type of replacement supply air outlets
- Air velocities near the hood
- Distance from openings to spaces outside the laboratory
- Movements of the researcher within the hood opening
- Location, size, and type of research apparatus placed in the hood
- Distance from the apparatus to the researcher's breathing zone

Air Currents. Air currents external to the fume hood can jeopardize the hood's effectiveness and expose the researcher to materials used in the hood. Detrimental air currents can be produced by

- Air supply distribution patterns in the laboratory
- Movements of the researcher
- People walking past the fume hood
- Thermal convection
- Opening of doors and windows

Caplan and Knutson (1977, 1978) conducted tests to determine the interactions between room air motion and fume hood capture velocities with respect to the spillage of contaminants into the room. Their tests indicated that the effect of room air currents is significant and of the same order of magnitude as the effect of the hood face velocity. Consequently, improper design and/or installation of the replacement air supply can lower the performance of the fume hood.

Disturbance velocities at the face of the hood should be no more than one-half and preferably one-fifth the face velocity of the hood. This is an especially critical factor in designs that use low face velocities. For example, a fume hood with a face velocity of 100 fpm could tolerate a maximum disturbance velocity of 50 fpm. If the design face velocity were 60 fpm, the maximum disturbance velocity would be 30 fpm.

To the extent possible, the fume hood should be located so that traffic flow past the hood is minimal. Also, the fume hood should be placed to avoid any air currents generated from the opening of windows and doors. To ensure the optimum placement of the fume hoods, the HVAC system designer must take an active role early in the design process.

Use of Auxiliary Air Fume Hoods. AIHA *Standard* Z9.5 discourages the use of auxiliary air fume hoods. These hoods incorporate an air supply at the fume hood to reduce the amount of room air exhausted. The following difficulties and installation criteria are associated with auxiliary air fume hoods:

- The auxiliary air supply must be introduced outside the fume hood to maintain appropriate velocities past the researcher.
- The flow pattern of the auxiliary air must not degrade the containment performance of the fume hood.
- Auxiliary air must be conditioned to avoid blowing cold air on the researcher; often the air must be cooled to maintain the required temperature and humidity within the hood. Auxiliary air can introduce additional heating and cooling loads in the laboratory.
- Only vertical sash should be used in the hood.
- Controls for the exhaust, auxiliary, and supply airstreams must be coordinated.

- Additional coordination of utilities during installation is required to avoid spatial conflicts caused by the additional duct system.
- Humidity control can be difficult: Unless auxiliary air is cooled to the dew point of the specified internal conditions, there is some degradation of humidity control; however, if such cooling is done, the rationale for using auxiliary air has been eliminated.

Fume Hood Performance Criteria. ASHRAE *Standard* 110, Method of Testing Performance of Laboratory Fume Hoods, describes a quantitative method of determining the containment performance of a fume hood. The method requires the use of a tracer gas and instruments to measure the amount of tracer gas that enters the breathing zone of a mannequin; this simulates the containment capability of the fume hood as a researcher conducts operations in the hood. The following tests are commonly used to judge the performance of the fume hood: (1) face velocity test, (2) flow visualization test, (3) large-volume flow visualization, (4) tracer gas test, and (5) sash movement test. These tests should be performed under the following conditions:

- Usual amount of research equipment in the hood; the room air balance set
- Doors and windows in their normal positions
- Fume hood sash set in varying positions to simulate both static and dynamic performance

All fume hoods should be tested annually and their performance certified. The following descriptions partially summarize the test procedures. ASHRAE *Standard* 110 provides specific requirements and procedures.

Face Velocity Test

The safety officer, engineer, and the researcher should determine the desired face velocity. The velocity is a balance between safe operation of the fume hood, airflow needed for the hood operation, and energy cost. Face velocity measurements are taken on a vertical/horizontal grid, with each measurement point representing not more than 1 ft^2. The measurements should be taken with a device that is accurate in the intended operating range, and an instrument holder should be used to improve accuracy. Computerized multipoint grid measurement devices provide the greatest accuracy.

Flow Visualization

1. Swab a strip of titanium tetrachloride along both walls and the hood deck in a line parallel to the hood face and 6 in. back into the hood. *Caution*: Titanium tetrachloride forms smoke and is corrosive to the skin and extremely irritating to the eyes and respiratory system.
2. Swab an 8 in. circle on the back of the hood. Define air movement toward the face of the hood as reverse airflow and lack of movement as dead airspace.
3. Swab the work surface of the hood, being sure to swab lines around all equipment in the hood. All smoke should be carried to the back of the hood and out.
4. Test the operation of the deck airfoil bypass by running the cotton swab under the airfoil.
5. Before going to the next test, move the cotton swab around the face of the hood; if there is any outfall, the exhaust capacity test (large capacity flow visualization) should not be made.

Large-Volume Flow Visualization

Appropriate measures should be taken prior to undertaking a smoke test to avoid accidental activation of the building's smoke detection system.

1. Ignite and place a smoke generator near the center of the work surface 6 in. behind the sash. Some smoke sources generate a jet of smoke that produces an unacceptably high challenge to the hood. Care is required to ensure that the generator does not disrupt the hood performance, leading to erroneous conclusions.

FRONT VIEW   **END VIEW**

CLASS I

HEPA EXHAUST FILTER
SUPPLY AIR DIFFUSER
EXHAUST AIR PLENUM
HEPA FILTER

FRONT VIEW   **END VIEW**

CLASS II TYPE B

HEPA EXHAUST FILTER
HEPA SUPPLY FILTER

FRONT VIEW   **END VIEW**

CLASS II TYPE A

EXHAUST   INTAKE   EXHAUST

FRONT VIEW   **END VIEW**

CLASS III
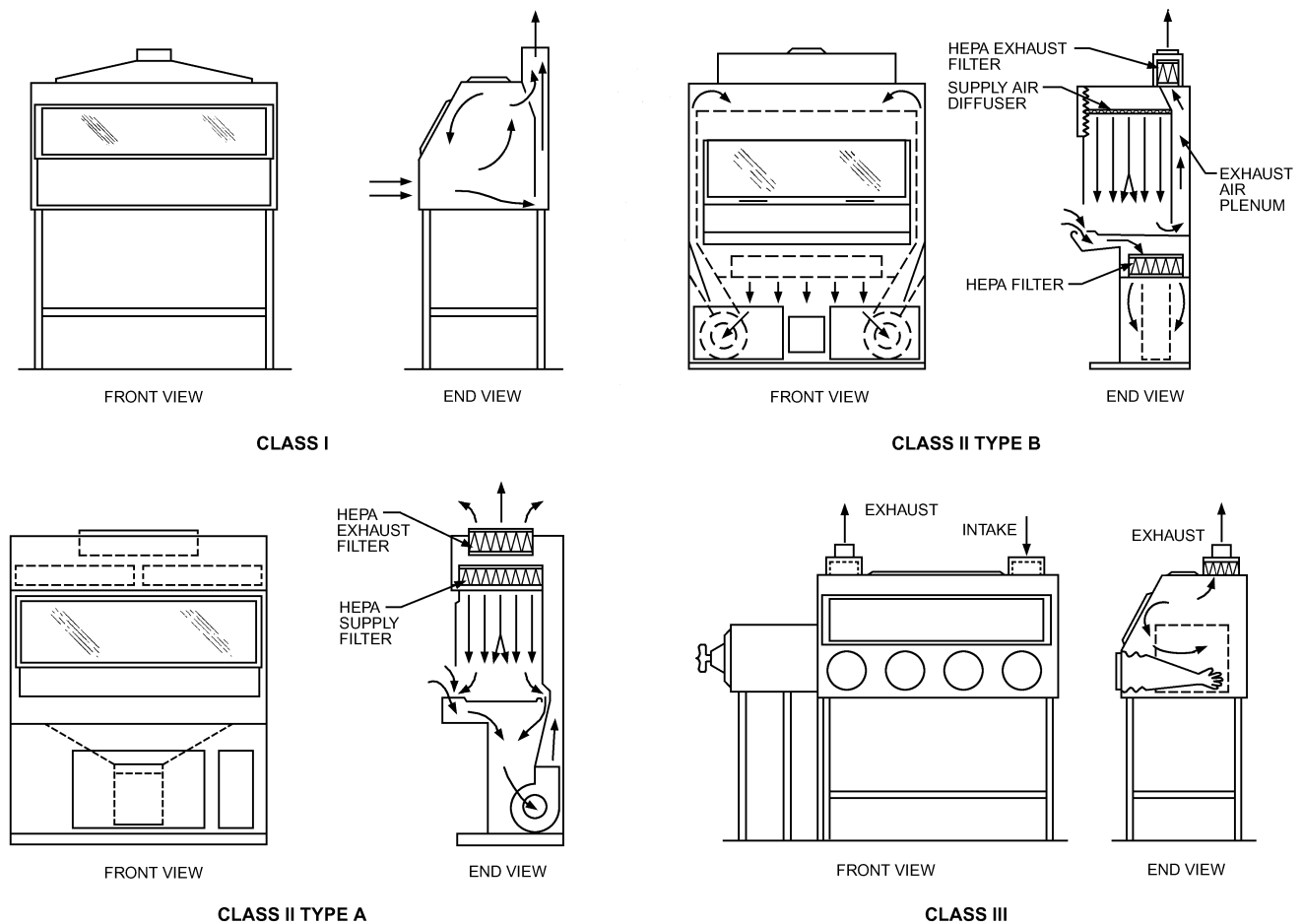
Fig. 2   Types of Biological Safety Cabinets

2. After the smoke bomb is ignited, pick it up with tongs and move it around the hood. The smoke should not be seen or smelled outside the hood.

Tracer Gas Test

1. Place the sulfur hexafluoride gas ejector in the required test locations (i.e., the center and near each side). Similarly position a mannequin with a detector in its breathing zone in the corresponding location at the hood.

2. Release the tracer gas and record measurements over a 5 min time span.

3. After testing with the mannequin is complete, remove it, traverse the hood opening with the detector probe, and record the highest measurement.

Sash Movement Test

Verify containment performance of the fume during operation of the fume hood sash as described in ASHRAE *Standard* 110.

BIOLOGICAL SAFETY CABINETS

A biological safety cabinet protects the researcher and, in some configurations, the research materials as well. Biological safety cabinets are sometimes called safety cabinets, ventilated safety cabinets, laminar flow cabinets, and glove boxes. Biological safety

cabinets are categorized into six groups (several are shown in Figure 2):

Class I   Similar to chemical fume hood, no research material protection, 100% exhaust through a HEPA filter

Class II

Type A1   70% recirculation within the cabinet; 30% exhaust through a HEPA filter; common plenum configuration; can be recirculated into the laboratory

Type B1   30% recirculation within the cabinet; 70% exhaust through a HEPA filter; separate plenum configuration, must be exhausted to the outside

Type B2   100% exhaust through a HEPA filter to the outside

Type A2   70% recirculation within the cabinet; 30% exhaust through a HEPA filter; common plenum configuration; must be exhausted to the outside

Class III   Special applications; 100% exhaust through a HEPA filter to the outside; researcher manipulates material within cabinet through physical barriers (gloves)

The researcher must make several key decisions before selecting a biological safety cabinet (Eagleston 1984). An important difference in biological safety cabinets is their ability to handle chemical vapors properly (Stuart et al. 1983). Of special concern to the HVAC engineer are the proper placement of the biological safety cabinet in

the laboratory and the room's air distribution. Rake (1978) concluded the following:

> A general rule of thumb should be that, if the cross draft or other disruptive room airflow exceeds the velocity of the air curtain at the unit's face, then problems do exist. Unfortunately, in most laboratories such disruptive room airflows are present to various extents. Drafts from open windows and doors are the most hazardous sources because they can be far in excess of 200 fpm and accompanied by substantial turbulence. Heating and air-conditioning vents perhaps pose the greatest threat to the safety cabinet because they are much less obvious and therefore seldom considered. . . . It is imperative then that all room airflow sources and patterns be considered before laboratory installation of a safety cabinet.

Class II biological safety cabinets should only be placed in the laboratory in compliance with NSF International *Standard* 49, Class II (Laminar Flow) Biohazard Cabinetry. Assistance in procuring, testing, and evaluating performance parameters of Class II biological safety cabinets is available from NSF as part of the standard. The cabinets should be located away from drafts, active walkways, and doors. The air distribution system should be designed to avoid air patterns that impinge on the cabinet.

The different biological safety cabinets have varying static pressure resistance requirements. Generally, Class II Type A1 cabinets have pressure drops ranging between 0.005 and 0.1 in. of water. Class II Type B1 cabinets have pressure drops in the range of 0.6 to 1.2 in. of water, and Class II Type B2 cabinets have pressure drops ranging from 1.5 to 2.3 in. of water. The manufacturer must be consulted to verify specific requirements.

The pressure requirements also vary based on filter loading and the intermittent operation of individual biological safety cabinets. Exhaust systems for biological safety cabinets must be designed with these considerations in mind. Care must be exercised when manifolding biological safety cabinet exhausts to ensure that the varying pressure requirements are met.

The manufacturer of the biological safety cabinet may be able to supply the transition to the duct system. The transition should include an access port for testing and balancing and an airtight damper for decontamination. As with any containment ductwork, high-integrity duct fabrication and joining systems are necessary.

Biological safety cabinets may require periodic decontamination before service and filter replacement. During the decontamination procedure, the cabinet must be isolated or sealed from the laboratory and the exhaust system. The responsible safety officer should be consulted to determine the need for and placement of isolation dampers to facilitate decontamination operations. If provisions for decontamination are necessary, the ventilation system design should maintain laboratory airflow and pressure during the decontamination procedure.

Class I Cabinets

The Class I cabinet is a partial containment device designed for research operations with low- and moderate-risk etiologic agents. It does not provide protection for the materials used in the cabinet. Room air flows through a fixed opening and prevents aerosols that may be generated within the cabinet enclosure from escaping into the room. Depending on cabinet usage, air exhausted through the cabinet may be HEPA filtered prior to being discharged into the exhaust system. The fixed opening through which the researcher works is usually 8 in. high. To provide adequate personnel protection, the air velocity through the fixed opening is usually at least 75 fpm.

If approved by the appropriate safety officer, it is possible to modify the Class I cabinet to contain chemical carcinogens by adding appropriate exhaust air treatment and increasing the velocity through the opening to 100 fpm. Large pieces of research equipment can be placed in the cabinet if adequate shielding is provided.

The Class I cabinet is not appropriate for containing systems that are vulnerable to airborne contamination because the air flowing into the cabinet is untreated. Also, the Class I cabinet is not recommended for use with highly infectious agents because an interruption of the inward airflow may allow aerosolized particles to escape.

Class II Cabinets

Class II cabinets provide protection to personnel, product, and the environment. The cabinets feature an open front with inward airflow and HEPA-filtered recirculated and exhaust air. Microbiological containment, product protection, and cross-contamination performance is established for certain cabinets by NSF International's *Standard* 49.

The Class II Type A1 cabinet has a fixed opening with a minimum inward airflow velocity of 75 fpm. The average downward velocity is established by the manufacturer and is typically in the range of 50 to 80 fpm. The Class II Type A1 cabinet is suitable for use with agents meeting Biosafety Level 2 criteria (DHHS 1999), and, if properly certified, can meet Biosafety Level 3. However, because approximately 70% of the airflow is recirculated, the cabinet is not suitable for use with flammable, toxic, or radioactive agents.

The Class II Type B1 cabinet has a vertical sliding sash and maintains an inward airflow of 100 fpm at a sash opening of 8 in. The average downward velocity of the internal airflow is typically in the range of 50 to 80 fpm. The Class II Type B1 cabinet is suitable for use with agents meeting Biosafety Level 3. Approximately 70% of the internal airflow is exhausted through HEPA filters; this allows the use of biological agents treated with limited quantities of toxic chemicals and trace amounts of radionuclides, provided the work is performed in the direct exhaust area of the cabinet.

The Class II Type B2 cabinet maintains an inward airflow velocity of 100 fpm through the work opening. The cabinet is 100% exhausted through HEPA filters to the outdoors; all downward-velocity air is drawn from the laboratory or other supply source and is HEPA filtered before being introduced into the workspace. The Class II Type B2 cabinet may be used for the same level of work as the Class II Type B1 cabinet. In addition, the design permits use of toxic chemicals and radionuclides in microbiological studies.

The Class II Type A2 cabinet maintains an inward airflow velocity of 100 fpm and is similar in performance to the Class II Type A1 cabinet.

In Class II Type A2 cabinets, exhaust air delivered to the outlet of the cabinet by internal blowers must be handled by the laboratory exhaust system. This arrangement requires a delicate balance between the cabinet and the laboratory's exhaust system, and it may incorporate a thimble connection between the cabinet and the laboratory exhaust ductwork. Thimble (or canopy) connections incorporate an air gap between the biological safety cabinet and the exhaust duct. The purpose of the air gap is to buffer the effect of any exhaust system fluctuations on the biological safety cabinet airflow. The exhaust system must pull more air than is exhausted by the biological safety cabinet to make air flow in through the gap. The designer should confirm the amount of air to be drawn through the air gap. A minimum flow is required to provide the specified level of containment, and a maximum flow cannot be exceeded without causing an imbalance through aspiration. In the event of an exhaust system failure, the air gap allows the cabinet to maintain safe intake velocity by exhausting HEPA-filtered air through the air gap.

Class II Type B1 and Type B2 cabinets rely on the building exhaust system to pull the air from the cabinet's workspace and through the exhaust HEPA filters. The pressure resistance that must be overcome by the building exhaust system can be obtained from the cabinet manufacturer. Because containment in this type of cabinet depends on the building's exhaust system, the exhaust fan(s) should have redundant backups.

Class III Cabinets

The Class III cabinet is a gastight, negative pressure containment system that physically separates the agent from the worker. These cabinets provide the highest degree of personnel protection. Work is performed through arm-length rubber gloves attached to a sealed front panel. Room air is drawn into the cabinet through HEPA filters. Class III cabinets should be maintained at 0.5 in. of water below ambient pressure. Exhaust flow rate should provide a minimum of 100 fpm inward containment velocity through a glove port opening in the event of a glove being inadvertently removed. HEPA filtration or incineration before discharge to the atmosphere removes or destroys particulate material entrained in the exhaust air. A Class III system may be designed to enclose and isolate incubators, refrigerators, freezers, centrifuges, and other research equipment. Double-door autoclaves, liquid disinfectant dunk tanks, and pass boxes are used to transfer materials into and out of the cabinet.

Class III systems can contain highly infectious materials and radioactive contaminants. Although there are operational inconveniences with these cabinets, they are the equipment of choice when a high degree of personnel protection is required. It should be noted that explosions have occurred in Class III cabinets used for research involving volatile substances.

MISCELLANEOUS EXHAUST DEVICES

Snorkels are used in laboratories to remove heat or nontoxic particles that may be generated from benchtop research equipment. Snorkels usually have funnel-shaped inlet cones connected to 3 to 6 in. diameter flexible or semi-flexible ductwork extending from the ceiling to above the benchtop level.

Typically, **canopy hoods** are used to remove heat or moisture generated by a specific piece of research apparatus (e.g., steam sterilizer) or process. Canopy hoods cannot contain hazardous fumes adequately to protect the researcher.

The laboratory, if maintained at negative relative static pressure, provides a second level of containment, protecting occupied spaces outside of the laboratory from operations and processes undertaken therein.

LAMINAR FLOW CLEAN BENCHES

Laminar flow clean benches are available in two configurations—horizontal (crossflow) and vertical (downflow). Both configurations filter the supply air and usually discharge the air out the front opening into the room. Clean benches protect the experiment or product but do not protect the researcher; therefore, they should not be used with any potentially hazardous or allergenic substances. Clean benches are not recommended for any work involving hazardous biological, chemical, or radionuclide materials.

COMPRESSED GAS STORAGE AND VENTILATION

Gas Cylinder Closets

Most laboratory buildings require storage closets for cylinders of compressed gases, which may be inert, flammable, toxic, corrosive, or poisonous. The requirements for storage and ventilation are covered in building codes and NFPA standards and codes. Water sprinklers are usually required, but other types of fire suppression may be needed based on the gases stored. Explosion containment requires a separate structural study, and closets generally require an outside wall for venting. One design used by a large chemical manufacturer to house gases with explosion potential specifies a completely welded 0.25 in. steel inner liner for the closet, heavy-duty door latches designed to hold under the force of an internal explosion, and venting out the top of the closet.

The closet temperature should not exceed 125°F per NFPA *Standard* 55. Ventilation for cylinder storage is established in NFPA *Standard* 55 at a minimum of 1 cfm/ft^2. Ventilation rates can be calculated by determining both the amount of gas that could be released by complete failure of the cylinder outlet piping connection and the time the release would take, and then finding the dilution airflow required to reduce any hazard below the maximum allowable limit. Design principles for biohazardous materials may be different than for chemical hazards. An investigation for biohazard containment can start with NFPA *Standard* 99, Health Care Facilities.

Ventilation air is usually exhausted from the closet; makeup air comes from the surrounding space through openings in and around the door or through a transfer duct. That makeup air must be added into the building air balance. Ventilation for a closet to contain materials with explosion potential must be carefully designed, with safety considerations taken into account. NFPA *Standard* 68 is a reference on explosion venting.

Cylinder closet exhausts should be connected through a separate duct system to a dedicated exhaust fan or to a manifold system in which constant volume can be maintained under any possible manifold condition. A standby source of emergency power should be considered for the exhaust system fan(s).

Gas Cylinder Cabinets

Compressed gases that present a physical or health hazard are often placed in premanufactured gas cylinder cabinets. Gas cylinder cabinets are available for single-, dual-, or triple-cylinder configurations and are commonly equipped with valve manifolds, fire sprinklers, exhaust connections, access openings, and operational and safety controls. The engineer must fully understand safety, material, and purity requirements associated with specific compressed gases when designing and selecting cylinder cabinets and the components that make up the compressed gas handling system.

Exhaust from the gas cylinder cabinets is provided at a high rate. Air is drawn into the gas cylinder cabinet from the surrounding space through a filtered opening, usually on the lower front of the cylinder cabinet. Depending on the specific gas in the cabinet, the exhaust system may require emission control equipment and a source of emergency power.

LABORATORY VENTILATION

The total airflow rate for a laboratory is dictated by one of the following:

- Total amount of exhaust from containment and exhaust devices
- Cooling required to offset internal heat gains
- Minimum ventilation rate requirements

Fume hood exhaust requirements (including evaluation of alternate sash configurations as described in the section on Fume Hoods) must be determined in consultation with the safety officers. The HVAC engineer must determine the expected heat gains from the research equipment after consulting with the research staff (see the section on Internal Thermal Considerations).

Minimum airflow rates are generally in the range of 6 to 10 air changes per hour when the space is occupied; however, some spaces (e.g., animal holding areas) may have minimum airflow rates established by specific standards or by internal facility policies. For example, the National Institutes of Health (NIH 1999a, 1999b) recommend a minimum of 6 air changes per hour for occupied laboratories but a minimum of 15 air changes per hour for animal housing and treatment areas. The maximum airflow rate for the laboratory should be reviewed to ensure that appropriate supply air delivery methods are chosen such that supply airflows do not impede the performance of the exhaust devices. Laboratory ventilation systems can be arranged for either constant-volume or variable-volume airflow. The specific type should be selected with the research staff,

safety officers, and maintenance personnel. Special attention should be given to unique areas such as glass washing areas, hot and cold environmental rooms and labs, fermentation rooms, and cage washing rooms. Emergency power systems to operate the laboratory ventilation equipment should be considered based on hazard assessment or other specific requirements. Care should be taken to ensure that an adequate amount of makeup air is available whenever exhaust fans are operated on emergency power. Additional selection criteria are described in the sections on Hazard Assessment and Operation and Maintenance.

Usage Factor

In many laboratories, all hoods and safety cabinets are seldom needed at the same time. A system usage factor represents the maximum number of exhaust devices with sashes open or in use simultaneously. The system usage factor depends on the

- Type and size of facility
- Total number of fume hoods
- Number of fume hoods per researcher
- Airflow diversity
- Type of fume hood controls
- Fume hood sash configuration and minimum airflow required
- Type of laboratory ventilation systems
- Number of devices that must operate continuously due to chemical storage requirements or contamination prevention
- Number of current and projected research programs

Usage factors should be applied carefully when sizing equipment. For example, teaching laboratories may have a usage factor of 100% when occupied by students.

If too low a usage factor is selected, design airflow and containment performance cannot be maintained. It is usually expensive and disruptive to add capacity to an operating laboratory's supply or exhaust system. Detailed discussions with research staff are required to ascertain maximum usage factors as well as likely future requirements.

Noise

Noise level in the laboratory should be considered at the beginning of the design so that noise criterion (NC) levels suitable for scientific work can be achieved. For example, at the NIH, sound levels of NC 40 to 45 (including fume hoods) are required in regularly occupied laboratories. The requirement is relaxed to NC 55 for instrument rooms. If noise criteria are not addressed as part of the design, NC levels can be 65 or greater, which is unacceptable to most occupants. Sound generated by the building HVAC equipment should be evaluated to ensure that excessive levels do not escape to the outdoors. Remedial correction of excessive sound levels can be difficult and expensive. See Chapter 47 for more information.

SUPPLY AIR SYSTEMS

Supply air systems for laboratories provide the following:

- Thermal comfort for occupants
- Minimum and maximum airflow rates
- Replacement for air exhausted through fume hoods, biological safety cabinets, or other exhaust devices
- Space pressurization control
- Environmental control to meet process or experimental criteria

The design parameters must be well defined for selection, sizing, and layout of the supply air system. Installation and setup should be verified as part of the commissioning process. Design parameters are covered in the section on Design Parameters, and commissioning is covered in the section on Commissioning. Laboratories in

which chemicals and compressed gases are used generally require nonrecirculating or 100% outside air supply systems. The selection of 100% outside air supply systems versus return air systems should be made as part of the hazard assessment process, which is discussed in the section on Hazard Assessment. A 100% outside air system must have a very wide range of heating and cooling capacity, which requires special design and control.

Supply air systems for laboratories include constant-volume, high-low volume, and variable-volume systems that incorporate either single-duct reheat or dual-duct configurations, with distribution through low-, medium-, or high-pressure ductwork.

Filtration

Filtration for the air supply depends on the requirements of the laboratory. Conventional chemistry and physics laboratories commonly use 85% dust spot efficient filters (ASHRAE *Standard* 52.1). Biological and biomedical laboratories usually require 85 to 95% dust spot efficient filtration. HEPA filters should be provided for spaces where research materials or animals are particularly susceptible to contamination from external sources. HEPA filtration of the supply air is necessary for such applications as environmental studies, studies involving specific pathogen-free research animals or nude mice, dust-sensitive work, and electronic assemblies. In many instances, biological safety cabinets or laminar flow clean benches (which are HEPA filtered) may be used rather than HEPA filtration for the entire laboratory.

Air Distribution

Air supplied to a laboratory must be distributed to keep temperature gradients and air currents to minimum. Air outlets (preferably nonaspirating diffusers) must not discharge into the face of a fume hood, a biological safety cabinet, or an exhaust device. Acceptable room air velocities are covered in the sections on Fume Hoods and Biological Safety Cabinets. Special techniques and diffusers are often needed to introduce the large air quantities required for a laboratory without creating disturbances at exhaust devices.

EXHAUST SYSTEMS

Laboratory exhaust systems remove air from containment devices and from the laboratory itself. The exhaust system must be controlled and coordinated with the supply air system to maintain correct pressurization. Additional information on the control of exhaust systems is included in the section on Control. Design parameters must be well defined for selection, sizing, and layout of the exhaust air system. Installation and setup should be verified as part of the commissioning process. See the sections on Design Parameters and Commissioning. Laboratory exhaust systems should be designed for high reliability and ease of maintenance. This can be achieved by providing multiple exhaust fans that are not necessarily redundant or by sectionalizing equipment so that maintenance work may be performed on an individual exhaust fan while the system is operating. Another option is to use predictive maintenance procedures to detect problems prior to failure and to allow for scheduled shutdowns for maintenance. To the extent possible, components of exhaust systems should allow maintenance without exposing maintenance personnel to the exhaust airstream. Access to filters and the need for bag-in, bag-out filter housings should be considered during the design process.

Depending on the effluent of the processes being conducted, the exhaust airstream may require filtration, scrubbing, or other emission control to remove environmentally hazardous materials. Any need for emission control devices must be determined early in the design so that adequate space can be provided and cost implications can be recognized.

Types of Exhaust Systems

Laboratory exhaust systems can be constant-volume, variable-volume, or high-low volume systems with low-, medium-, or high-pressure ductwork, depending on the static pressure of the system. Each fume hood may have its own exhaust fan, or fume hoods may be manifolded and connected to one or more common central exhaust fans. Maintenance, functional requirements, and safety must be considered when selecting an exhaust system. Part of the hazard assessment analysis is to determine the appropriateness of variable-volume systems and the need for individually ducted exhaust systems. Laboratories with a high hazard potential should be analyzed carefully before variable-volume airflow is selected, because minimum air flow requirements could affect the design criteria. Airflow monitoring and pressure-independent control may be required even with constant-volume systems. In addition, fume hoods or other devices in which extremely hazardous or radioactive materials are used should receive special review to determine whether they should be connected to a manifolded exhaust system.

All exhaust devices installed in a laboratory are seldom used simultaneously at full capacity. This allows the HVAC engineer to conserve energy and, potentially, to reduce equipment capacities by installing a variable-volume system that includes an overall system usage factor. The selection of an appropriate usage factor is discussed in the section on Usage Factor.

Manifolded Exhaust Systems. These can be classified as pressure-dependent or pressure-independent. **Pressure-dependent systems** are constant-volume only and incorporate manually adjusted balancing dampers for each exhaust device. If an additional fume hood is added to a pressure-dependent exhaust system, the entire system must be rebalanced, and the speed of the exhaust fans may need to be adjusted. Because pressure-independent systems are more flexible, pressure-dependent systems are not common in current designs.

A **pressure-independent system** can be constant-volume, variable-volume, or a mix of the two. It incorporates pressure-independent volume regulators with each device. The system offers two advantages: (1) the flexibility to add exhaust devices without having to rebalance the entire system and (2) variable-volume control.

The volume regulators can incorporate either direct measurement of the exhaust airflow rate or positioning of a calibrated pressure-independent air valve. The input to the volume regulator can be (1) a manual or timed switch to index the fume hood airflow from minimum to operational airflow, (2) sash position sensors, (3) fume hood cabinet pressure sensors, or (4) velocity sensors. The section on Control covers this topic in greater detail. Running many exhaust devices into the manifold of a common exhaust system offers the following potential benefits:

- Lower ductwork cost
- Fewer pieces of equipment to operate and maintain
- Fewer roof penetrations and exhaust stacks
- Opportunity for energy recovery
- Centralized locations for exhaust discharge
- Ability to take advantage of exhaust system diversity
- Ability to provide a redundant exhaust system by adding one spare fan per manifold

Individually Ducted Exhaust Systems. These comprise a separate duct, exhaust fan, and discharge stack for each exhaust device or laboratory. The exhaust fan can be single-speed, multiple-speed, or variable-speed and can be configured for constant volume, variable volume, or a combination of the two. An individually ducted exhaust system has the following potential benefits:

- Provision for installation of special exhaust filtration or treatment systems

- Customized ductwork and exhaust fan corrosion control for specific applications
- Provision for selected emergency power backup
- Simpler initial balancing

Maintaining correct flow at each exhaust fan requires (1) periodic maintenance and balancing and (2) consideration of the flow rates with the fume hood sash in different positions. One problem encountered with individually ducted exhaust systems occurs when an exhaust fan is shut down. In this case, air can be drawn in reverse flow through the exhaust ductwork into the laboratory because the laboratory is maintained at a negative pressure.

A challenge in designing independently ducted exhaust systems for multistory buildings is to provide extra vertical ductwork, extra space, and other provisions for the future installation of additional exhaust devices. In multistory buildings, dedicated fire-rated shafts may be required from each floor to the penthouse or roof level. This issue should be evaluated in conjunction with the requirements of the relevant fire code. As a result, individually ducted exhaust systems (or vertically manifolded systems) consume greater floor space than horizontally manifolded systems. However, less height between floors may be required.

Ductwork Leakage

Ductwork should have low leakage rates and should be tested to confirm that the specified leakage rates have been attained. Leaks from positive pressure exhaust ductwork can contaminate the building, so they must be kept to a minimum. Designs that minimize the amount of positive-pressure ductwork are desirable. All positive-pressure ductwork should be of the highest possible integrity. The fan discharge should connect directly to the vertical discharge stack. Careful selection and proper installation of airtight flexible connectors at the exhaust fans are essential. Some feel that flexible connectors should be used on the exhaust fan inlet only. If flexible connectors are used on the discharge side of the exhaust fan, they must be of high quality and included on a preventative maintenance schedule because a connector failure could result in the leakage of hazardous fumes into the equipment room. Another viewpoint contends that the discharge side of the exhaust fan should be hard connected to the ductwork without the use of flexible connectors. The engineer should evaluate these details carefully. The potential for vibration and noise transmission must also be considered. Machine rooms that house exhaust fans should be ventilated to minimize exposure to exhaust effluent (e.g., leakage from the shaft openings of exhaust fans).

Containment Device Leakage

Leakage of the containment devices themselves must also be considered. For example, in vertical sash fume hoods, the clearance to allow sash movement creates an opening from the top of the fume hood into the ceiling space or area above. The air introduced through this leakage path also contributes to the exhaust airstream. The amount that such leakage sources contribute to the exhaust airflow depends on the fume hood design. Edge seals can be placed around sash tracks to minimize leaks. Although the volumetric flow of air exhausted through a fume hood is based on the actual face opening, appropriate allowances for air introduced through paths other than the face opening must be included.

Materials and Construction

The selection of materials and the construction of exhaust ductwork and fans depend on the following:

- Nature of the effluents
- Ambient temperature
- Ambient relative humidity
- Effluent temperature
- Length and arrangement of duct runs

- Constant or intermittent flow
- Flame spread and smoke developed ratings
- Duct velocities and pressures

Effluents may be classified generically as organic or inorganic chemical gases, vapors, fumes, or smoke; and qualitatively as acids, alkalis (bases), solvents, or oils. Exhaust system ducts, fans, dampers, flow sensors, and coatings are subject to (1) corrosion, which destroys metal by chemical or electrochemical action; (2) dissolution, which destroys materials such as coatings and plastics; and (3) melting, which can occur in certain plastics and coatings at elevated temperatures.

Common reagents used in laboratories include acids and bases. Common organic chemicals include acetone, ether, petroleum ether, chloroform, and acetic acid. The HVAC engineer should consult with the safety officer and scientists because the specific research to be conducted determines the chemicals used and therefore the necessary duct material and construction.

The ambient temperature in the space housing the ductwork and fans affects the condensation of vapors in the exhaust system. Condensation contributes to the corrosion of metals, and the chemicals used in the laboratory may further accelerate corrosion.

Ducts are less subject to corrosion when runs are short and direct, the flow is maintained at reasonable velocities, and condensation is avoided. Horizontal ductwork may be more susceptible to corrosion if condensate accumulates in the bottom of the duct. Applications with moist airstreams (cage washers, sterilizers, etc.) may require condensate drains that are connected to chemical sewers. The design should include provisions to minimize joint or seam corrosion problems.

If flow through the ductwork is intermittent, condensate may remain for longer periods because it will not be able to reevaporate into the airstream. Moisture can also condense on the outside of ductwork exhausting cold environmental rooms.

Flame spread and smoke developed ratings, which are specified by codes or insurance underwriters, must also be considered when selecting duct materials. In determining the appropriate duct material and construction, the HVAC engineer should

- Determine the types of effluents (and possibly combinations) handled by the exhaust system
- Classify effluents as either organic or inorganic, and determine whether they occur in the gaseous, vapor, or liquid state
- Classify decontamination materials
- Determine the concentration of the reagents used and the temperature of the effluents at the hood exhaust port (this may be impossible in research laboratories)
- Estimate the highest possible dew point of the effluent
- Determine the ambient temperature of the space housing the exhaust system
- Estimate the degree to which condensation may occur
- Determine whether flow will be constant or intermittent (intermittent flow conditions may be improved by adding time delays to run the exhaust system long enough to dry the duct interior prior to shutdown)
- Determine whether insulation, watertight construction, or sloped and drained ductwork are required
- Select materials and construction most suited for the application

Considerations in selecting materials include resistance to chemical attack and corrosion, reaction to condensation, flame and smoke ratings, ease of installation, ease of repair or replacement, and maintenance costs.

Appropriate materials can be selected from standard references and by consulting with manufacturers of specific materials. Materials for chemical fume exhaust systems and their characteristics include the following:

Galvanized steel. Subject to acid and alkali attack, particularly at cut edges and under wet conditions; cannot be field welded without destroying galvanization; easily formed; low in cost.

Stainless steel. Subject to acid and chloride compound attack depending on the nickel and chromium content of the alloy. Relatively high in cost. The most common stainless steel alloys used for laboratory exhaust systems are 304 and 316. Cost increases with increasing chromium and nickel content.

Asphaltum-coated steel. Resistant to acids; subject to solvent and oil attack; high flame and smoke rating; base metal vulnerable when exposed by coating imperfections and cut edges; cannot be field welded without destroying galvanization; moderate cost.

Epoxy-coated steel. Epoxy phenolic resin coatings on mild black steel can be selected for particular characteristics and applications; they have been successfully applied for both specific and general use, but no one compound is inert or resistive to all effluents. Requires sand blasting to prepare the surface for a shop-applied coating, which should be specified as pinhole-free, and field touch-up of coating imperfections or damage caused by shipment and installation; cannot be field welded without destroying coating; cost is moderate.

Polyvinyl-coated galvanized steel. Subject to corrosion at cut edges; cannot be field welded; easily formed; moderate in cost.

Fiberglass. When additional glaze coats are used, this is particularly good for acid applications, including hydrofluoric acid. May require special fire-suppression provisions. Special attention to hanger types and spacing is needed to prevent damage.

Plastic materials. Have particular resistance to specific corrosive effluents; limitations include physical strength, flame spread and smoke developed rating, heat distortion, and high cost of fabrication. Special attention to hanger types and spacing is needed to prevent damage.

Borosilicate glass. For specialized systems with high exposure to certain chemicals such as chlorine.

FIRE SAFETY FOR VENTILATION SYSTEMS

Most local authorities have laws that incorporate NFPA *Standard* 45, Fire Protection for Laboratories Using Chemicals. Laboratories located in patient care buildings require fire standards based on NFPA *Standard* 99, Health Care Facilities. NFPA *Standard* 45 design criteria include the following:

Air balance. "The air pressure in the laboratory work areas shall be negative with respect to adjacent corridors and non-laboratory areas." (Para. 6-3.3)

Controls. "Controls and dampers . . . shall be of a type that, in the event of failure, will fail in an open position to assure a continuous draft." (Para. 6-5.7)

Diffuser locations. "The location of air supply diffusion devices shall be chosen to avoid air currents that would adversely affect performance of laboratory hoods. . . ." (Para. 6-3.4)

Fire dampers. "Automatic fire dampers shall not be used in laboratory hood exhaust systems. Fire detection and alarm systems shall not be interlocked to automatically shut down laboratory hood exhaust fans. . . ." (Para. 6-10.3)

Hood alarms. "A flow monitor shall be installed on each new laboratory hood." (Para. 6-8.7.1) "A flow monitor shall also be installed on existing hoods whenever any modifications or changes are made. . . ." (Para. 6-8.7.2)

Hood placement. "For new installations, laboratory hoods shall not be located adjacent to a single means of access or high traffic areas." (Para. 6-9.2).

Recirculation. "Air exhausted from laboratory hoods or other special local exhaust systems shall not be recirculated." (Para. 6-4.1) "Air exhausted from laboratory work areas shall not pass unducted through other areas." (Para. 6-4.3)

The designer should review the entire NFPA *Standard* 45 and local building codes to determine applicable requirements. Then the

designer should inform the other members of the design team of their responsibilities (such as proper fume hood placement). Incorrect placement of exhaust devices is a frequent design error and a common cause of costly redesign work.

CONTROL

Laboratory controls must regulate temperature and humidity, control and monitor laboratory safety devices that protect personnel, and control and monitor secondary safety barriers used to protect the environment outside the laboratory from laboratory operations (West 1978). Reliability, redundancy, accuracy, and monitoring are important factors in controlling the lab environment. Many laboratories require precise control of temperature, humidity, and airflows. Components of the control system must provide the necessary accuracy and corrosion resistance if they are exposed to corrosive environments. Laboratory controls should provide failsafe operation, which should be defined jointly with the safety officer. A fault tree can be developed to evaluate the impact of the failure of any control system component and to ensure that safe conditions are maintained.

Thermal Control

Temperature in laboratories with a constant-volume air supply is generally regulated with a thermostat that controls the position of a control valve on a reheat coil in the supply air. In laboratories with a variable-volume ventilation system, room exhaust device(s) are generally regulated as well. The room exhaust device(s) are modulated to handle greater airflow in the laboratory when additional cooling is needed. The exhaust device(s) may determine the total supply air quantity for the laboratory.

Most microprocessor-based laboratory control systems are able to use proportional-integral-derivative (PID) algorithms to eliminate the error between the measured temperature and the temperature set point. Anticipatory control strategies increase accuracy in temperature regulation by recognizing the increased reheat requirements associated with changes in the ventilation flow rates and adjusting the position of reheat control valves before the thermostat measures space temperature changes (Marsh 1988).

Constant Air Volume (CAV) Versus Variable Air Volume (VAV) Room Airflow Control

In the past, the only option for airflow in a laboratory setting was fixed airflow. Many laboratories used chemical fume hoods controlled by on-off switches located at the hood that significantly affected the actual air balance and airflow rate in the laboratory. Now, true CAV or VAV control can be successfully achieved. The question is which system is most appropriate for a contemporary laboratory.

Many laboratories that were considered CAV systems in the past were not truly constant. Even when the fume hoods operated continuously and were of the bypass type, considerable variations in airflow could occur. Variations in airflow resulted from

- Static pressure changes due to filter loading
- Wet or dry cooling coils
- Wear of fan belts that change fan speed
- Position of chemical fume hood sash or sashes
- Outside wind speed and direction
- Position of doors and windows

Current controls can achieve good conformance to the requirements of a CAV system, subject to normal deviations in control performance (i.e., the dead band characteristics of the controller and the hysteresis present in the control system). The same is true for VAV systems, although they are more complex. Systems may be either uncontrolled or controlled. An uncontrolled CAV system can be designed with no automatic controls associated with airflow

other than two-speed fan motors to reduce flow during unoccupied periods. These systems are balanced by means of manual dampers and adjustable drive pulleys. They provide reasonable airflow rates relating to design values but do not provide true CAV under varying conditions, maintain constant fume hood face velocity, or maintain relative static pressures in the spaces. For laboratories that are not considered hazardous and do not have stringent safety requirements, uncontrolled CAV may be satisfactory.

For laboratories housing potentially hazardous operations (i.e., involving toxic chemicals or biological hazards), a true CAV or VAV system ensures that proper airflow and room pressure relationships are maintained at all times. A true CAV system requires volume controls on the supply and exhaust systems.

The principal advantages of a VAV system are its ability to (1) ensure that the face velocities of chemical fume hoods are maintained within a set range and (2) reduce energy use by reducing laboratory airflow. The appropriate safety officer and the users should concur with the choice of a VAV system or a CAV system with reduced airflow during unoccupied periods. Consideration should be given to providing laboratory users with the ability to reset VAV systems to full airflow volume in the event of a chemical spill. Education of the laboratory occupants in proper use of the system is essential. The engineer should recognize that the use of variable-volume exhaust systems may result in higher concentrations of contaminants in the exhaust airstream, which may increase corrosion, which influences the selection of materials.

Room Pressure Control

In most experimental work, the laboratory apparatus or the biological vector is considered to be the primary method of containment. The facility is considered to be the secondary level of containment.

For the laboratory to act as a secondary containment barrier, the air pressure in the laboratory must be maintained slightly negative with respect to adjoining areas. Exceptions are sterile facilities or clean spaces that may need to be maintained at a positive pressure with respect to adjoining spaces. See Chapter 26, Nuclear Facilities, for examples of secondary containment for negative pressure control.

Proper isolation is accomplished through the air balance/pressure relationship to adjacent areas. The pressure relationship is either

- Negative, for hazardous isolation of hazardous or toxic operations (dirty operations), or
- Positive, for protective isolation of precious or delicate operations (clean operations).

Common methods of room pressure control include manual balancing, direct pressure, volumetric flow tracking, and cascade control. All methods modulate the same control variable—supply airflow rate; however, each method measures a different variable.

Direct Pressure Control. This method measures the pressure differential across the room envelope and adjusts the amount of supply air into the laboratory to maintain the required differential pressure. Challenges encountered include (1) maintaining the pressure differential when the laboratory door is open, (2) finding suitable sensor locations, (3) maintaining a well-sealed laboratory envelope, and (4) obtaining and maintaining accurate pressure sensing devices. The direct pressure control arrangement requires tightly constructed and compartmentalized facilities and may require a vestibule on entry/exit doors. Engineering parameters pertinent to envelope integrity and associated flow rates are difficult to predict.

Because direct pressure control works to maintain the pressure differential, the control system automatically reacts to transient disturbances. Entry/exit doors may need a switch to disable the control system when they are open. Pressure controls recognize and

compensate for unquantified disturbances such as stack effects, infiltration, and influences of other systems in the building. Expensive, complex controls are not required, but the controls must be sensitive and reliable. In non-corrosive environments, controls can support a combination of exhaust applications, and they are insensitive to minimum duct velocity conditions. Successful pressure control provides the desired directional airflow but cannot guarantee a specific volumetric flow differential.

Volumetric Flow Tracking Control. This method measures both the exhaust and supply airflow and controls the amount of supply air to maintain the desired pressure differential. Volumetric control requires that the air at each supply and exhaust point be controlled. It does not recognize or compensate for unquantified disturbances such as stack effects, infiltration, and influences of other systems in the building. Flow tracking is essentially independent of room door operation. Engineering parameters are easy to predict, and extremely tight construction is not required. Balancing is critical and must be addressed across the full operating range.

Controls may be located in corrosive and contaminated environments; however, the controls may be subject to fouling, corrosive attack, and/or loss of calibration. Flow measurement controls are sensitive to minimum duct velocity conditions. Volumetric control may not guarantee directional airflow.

Cascade Control. This method measures the pressure differential across the room envelope to reset the flow tracking differential set point. Cascade control includes the merits and problems of both direct pressure control and flow tracking control; however, first cost is greater and the control system is more complex to operate and maintain.

Fume Hood Control

Criteria for fume hood control differ depending on the type of hood. The exhaust volumetric flow is kept constant for standard, auxiliary air, and air-bypass fume hoods. In variable-volume fume hoods, the exhaust flow is varied to maintain a constant face velocity. Selection of the fume hood control method should be made in consultation with the safety officer.

Constant-volume fume hoods can further be split into either pressure-dependent or pressure-independent systems. Although simple in configuration, the pressure-dependent system is unable to adjust the damper position in response to any fluctuation in system pressure across the exhaust damper.

Variable-volume fume hood control strategies can be grouped into two categories. The first either measures the air velocity entering a small sensor in the wall of the fume hood or determines face velocity by other techniques. The measured variable is used to infer the average face velocity based on an initial calibration. This calculated face velocity is then used to modulate the exhaust flow rate to maintain the desired face velocity.

The second category of variable-volume fume hood control measures the fume hood sash opening and computes the exhaust flow requirement by multiplying the sash opening by the face velocity set point. The controller then adjusts the exhaust device (e.g., by a variable-frequency drive on the exhaust fan or a damper) to maintain the desired exhaust flow rate. The control system may measure the exhaust flow for closed-loop control, or it may not measure exhaust flow in an open-loop control by using linear calibrated flow control dampers.

STACK HEIGHTS AND AIR INTAKES

Laboratory exhaust stacks should release effluent to the atmosphere without producing undesirable high concentrations at fresh air intakes, operable doors and windows, and locations on or near the building where access is uncontrolled. Three primary factors that influence the proper disposal of effluent gases are stack/intake separation, stack height, and stack height plus momentum. Chapter 16 of the 2005 *ASHRAE Handbook—Fundamentals* covers the criteria and formulas to calculate the effects of these physical relationships. For complex buildings or buildings with unique terrain or other obstacles to the airflow around the building, either scale model wind tunnel testing or computational fluid dynamics should be considered. However, standard *k*-ε computational fluid dynamics methods as applied to airflow around buildings need further development (Murakami et al. 1996; Zhou and Stathopoulos 1996).

Stack/Intake Separation

Separation of the stack discharge and air intake locations allows the atmosphere to dilute the effluent. Separation is simple to calculate with the use of short to medium-height stacks; however, to achieve adequate atmospheric dilution of the effluent, greater separation than is physically possible may be required, and the building roof near the stack will be exposed to higher concentrations of the effluent.

Stack Height

Chapter 15 of the 1997 *ASHRAE Handbook—Fundamentals* describes a geometric method to determine the stack discharge height high enough above the turbulent zone around the building that little or no effluent gas impinges on air intakes of the emitting building. The technique is conservative and generally requires tall stacks that may be visually unacceptable or fail to meet building code or zoning requirements. Also, the technique does not ensure acceptably low concentrations of effluents at air intakes (e.g., if there are large releases of hazardous materials or elevated intake locations on nearby buildings). A minimum stack height of 10 ft is required by AIHA *Standard* Z9.5 and is recommended by Appendix A of NFPA *Standard* 45.

Stack Height plus Momentum

To increase the effective height of the exhaust stacks, both the volumetric flow and the discharge velocity can be increased to increase the discharge momentum (Momentum Flow = Density × Volumetric Flow × Velocity). The momentum of the large vertical flow in the emergent jet lifts the plume a substantial distance above the stack top, thereby reducing the physical height of the stack and making it easier to screen from view. This technique is particularly suitable when (1) many small exhaust streams can be clustered together or manifolded prior to the exhaust fan to provide the large volumetric flow and (2) outside air can be added through automatically controlled dampers to provide constant exhaust velocity under variable load. The drawbacks to the second arrangement are the amount of energy consumed to achieve the constant high velocity and the added complexity of the controls to maintain constant flow rates. Dilution equations presented in Chapter 16 of the 2005 *ASHRAE Handbook—Fundamentals* or mathematical plume analysis (e.g., Halitsky 1989) can be used to predict the performance of this arrangement, or performance can be validated through wind tunnel testing. Current mathematical procedures tend to have a high degree of uncertainty, and the results should be judged accordingly.

Architectural Screens

Rooftop architectural screens around exhaust stacks are known to adversely affect exhaust dispersion. In general, air intakes should not be placed within the same screen enclosure as laboratory exhausts. Petersen et al. (1997) describe a method of adjusting dilution predictions of Chapter 16 of the 2005 *ASHRAE Handbook—Fundamentals* using a stack height adjustment factor, which is essentially a function of screen porosity.

Criteria for Suitable Dilution

An example criterion based on Halitsky (1988) is that the release of 15 cfm of pure gas through any stack in a moderate wind (3 to

18 mph) from any direction with a near-neutral atmospheric stability (Pasquill Gifford Class C or D) must not produce concentrations exceeding 3 ppm at any air intake. This criterion is meant to simulate an accidental release such as would occur in a spill of an evaporating liquid or after the fracture of the neck of a small lecture bottle of gas in a fume hood.

The intent of this criterion is to limit the concentration of exhausted gases at the air intake locations to levels below the odor thresholds of gases released in fume hoods, excluding highly odorous gases such as mercaptans. Laboratories that use extremely hazardous substances should conduct a chemical-specific analysis based on published health limits. A more lenient limit may be justified for laboratories with low levels of chemical usage. Project-specific requirements must be developed in consultation with the safety officer. The equations in Chapter 16 of the 2005 *ASHRAE Handbook—Fundamentals* are presented in terms of dilution, defined as the ratio of stack exit concentration to receptor concentration. The exit concentration, and therefore the dilution required to meet the criterion, varies with the total volumetric flow rate of the exhaust stack. For the above criterion with the emission of 15 cfm of a pure gas, a small stack with a total flow rate of 1000 cfm will have an exit concentration of 15/1000 or 15,000 ppm. A dilution of 1:5000 is needed to achieve an intake concentration of 3 ppm. A larger stack with a flow rate of 10,000 cfm will have a lower exit concentration of 15/10,000 or 1500 ppm and would need a dilution of only 1:500 to achieve the 3 ppm intake concentration.

The above criterion is preferred over a simple dilution standard because a defined release scenario (15 cfm) is related to a defined intake concentration (3 ppm) based on odor thresholds or health limits. A simple dilution requirement may not yield safe intake concentrations for a stack with a low flow rate.

Adjacent Building Effects

The influence of adjacent building effects was studied under ASHRAE *Research Project* 897 (Wilson et al. 1998). Several guidelines were developed from this project:

- Designers should locate stacks near the edge of a roof.
- With the emitting building upwind, an adjacent building will always have higher dilution on a lower step-down roof than would occur on a flat roof at the emitting building's height. Ignoring the step-down in roof level will produce conservative designs.
- If the lower adjacent building is upwind of the emitting building, it will block flow approaching the emitting building, producing lower velocities and recirculation cavities on the emitting building roof and increasing dilution by factors of 2 to 10 on the emitting building.
- Designers should use increased exhaust velocity to produce jet dilution when the plume will be trapped in the recirculation cavity from a high upwind adjacent building.
- When the adjacent building is higher than the emitting building, designers should try to avoid placing air intakes on the adjacent building at heights above the roof level of the emitting building.

Also see Chapter 44, Building Air Intake and Exhaust Design, for more information.

APPLICATIONS

LABORATORY ANIMAL FACILITIES

Laboratory animals must be housed in comfortable, clean, temperature- and humidity-controlled rooms. Animal welfare must be considered in the design; the air-conditioning system must provide the macroenvironment for the animal room and the subsequent effect on the microenvironment in the animal's primary enclosure or cage specified by the facility's veterinarian (Besch 1975; ILAR

1996; Woods 1980). Early detailed discussions with the veterinarian concerning airflow patterns, cage layout, and risk assessment help ensure a successful animal room HVAC design. The elimination of research variables (fluctuating temperature and humidity, drafts, and spread of airborne diseases) is another reason for a high-quality air-conditioning system. See Chapter 22 for additional information on environments for laboratory animals.

Primary Uses of Animal Housing Facilities

Primary uses of animal facilities include the following:

- **Acute (short-term) studies:** generally less than 90 days in length, although the animal species and particular experiments involved could affect duration. Most frequently found in pharmaceutical, medical, or other life science laboratories, and includes
  - Assays and screens
  - Immune-suppressed animals
  - Pharmacology and metabolism
  - Infectious disease
- **Chronic (long-term) studies:** generally more than 90 days in length, although the species and experiment involved could affect the length. Includes
  - Toxicology
  - Teratology
  - Neurological
  - Quality control
- **Long-term holding of animals,** including
  - Production of materials used primarily in pharmaceuticals
  - Breeding
  - Laboratory animals
  - Companion animals
  - Food and fiber animals
- **Agricultural studies,** including food and fiber animals

Regulatory Environment

There are a number of regulations and guidelines that pertain to the housing of laboratory animals. Additional regulations cover the housing of animals that may be used some way in the production of pharmaceuticals, testing for agricultural products or used for quality control. The pertinent regulations are outlined below and are applied in the United States. Other countries have similar regulations that should be consulted when designing animal facilities located in that respective country. The regulations and guidelines include the following:

- Code of Federal Regulations (CFR) 21
  - Part 58; Good Laboratory Practices for Non-Clinical Laboratory Studies
  - Part 210; current Good Manufacturing Practice in Manufacture, Processing, Packing or Holding of Human and Veterinary Drugs
- Guide for the Care and Use of Laboratory Animals, National Research Council
- Biosafety in Microbiological and Biomedical Laboratories, Center for Disease Control (CDC).
- The Animal Welfare Act of 1966 and as subsequently amended. Regulatory authority is vested in the Secretary of the U.S. Department of Agriculture (USDA) and implemented by the USDA's Animal and Plant Health Inspection Service.
- American Association for Accreditation of Laboratory Animal Care (AAALAC), a nonprofit organization to which many institutions and corporations belong. This group provides accreditation based upon inspections and reports from member groups. Many organizations that build or maintain animal facilities adhere to AAALAC programs and HVAC engineers are expected to design to their guidelines.

Local ordinances or user organization requirements may also apply. HVAC engineers should confirm which regulations are applicable for any project.

Temperature and Humidity

Due to the nature of research programs, air-conditioning design temperature and humidity control points may be required. Research animal facilities require more precise environmental control than farm animal or production facilities because variations affect the experimental results. A totally flexible system permits control of the temperature of individual rooms to within ±2°F for any set point in a range of 64 to 85°F. This flexibility requires significant capital expenditure, which can be mitigated by designing the facility for selected species and their specific requirements.

Table 1 lists dry-bulb temperatures recommended by ILAR (1996) for several common species. In the case of animals in confined spaces, the range of daily temperature fluctuations should be kept to a minimum. Relative humidity should also be controlled. ASHRAE *Standard* 62 recommends that the relative humidity in habitable spaces be maintained between 30 and 60% to minimize growth of pathogenic organisms. ILAR (1996) suggests the acceptable range of relative humidity is 30 to 70%.

Ventilation

A guideline of 10 to 15 outside air changes per hour (ach) has been used for secondary enclosures for many years. Although it is effective in many settings, the guideline does not consider the range of possible heat loads; the species, size, and number of animals involved; the type of bedding or frequency of cage changing; the room dimensions; or the efficiency of air distribution from the secondary to the primary enclosure. In some situations, such a flow rate might overventilate a secondary enclosure that contains few animals and waste energy or underventilate a secondary enclosure that contains many animals and allow heat and odor to accumulate.

For small-animal caging systems, recent studies suggest that room conditions have very little influence on the cage environments. ASHRAE *Research Project* RP-730 (Riskowski et al. 1995, 1996) found the following:

- No relationship between room ventilation rate and cage microenvironments for shoebox and microisolator cages exists. In fact, 5 ach provided the same cage ventilation rates for shoebox cages as did 10 and 15 ach.
- Diffuser type (perforated square versus radial) had only a small effect on shoebox cage ventilation rates. The radial diffuser provided higher wire cage ventilation rates.
- One high return provided the same cage ventilation rates as four high returns or as one low return.
- Room size had no effect on cage ventilation rates.

This research is further discussed in Chapter 22.

In certain types of animal rooms, usually those used for long-term studies involving high-value work or animals, the outside air change rate is maintained at the 10 to 15 per hour but the total

airflow in the rooms ranges from 90 to 150 ach (mass flow spaces similar to clean rooms). The air supply is generally terminal-HEPA-filtered to reduce the potential for disease. These rooms are energy-intensive, and may not be required with the filter capability and caging systems available today.

The air-conditioning load and flow rate for an animal room should be determined by the following factors:

- Desired animal microenvironment (Besch 1975, 1980; ILAR 1996)
- Species of animal(s)
- Animal population
- Recommended ambient temperature (Table 1)
- Heat produced by motors on special animal housing units (e.g., laminar flow racks or HEPA-filtered air supply units for ventilated racks)
- Heat generated by the animals (Table 2)

Additional design factors include method of animal cage ventilation; operational use of a fume hood or a biological safety cabinet during procedures such as animal cage cleaning and animal examination; airborne contaminants (generated by animals, bedding, cage cleaning, and room cleaning); and institutional animal care standards (Besch 1980, ILAR 1996). It should be noted that the ambient conditions of the animal room might not reflect the actual conditions within a specific animal cage.

Animal Heat Production

Air-conditioning systems must remove the sensible and latent heat produced by laboratory animals. The literature concerning the metabolic heat production appears to be divergent, but new data are consistent. Current recommended values are given in Table 2. These values are based on experimental results and the following equation:

$$ATHG = 2.5M$$

where

ATHG = average total heat gain, Btu/h per animal
M = metabolic rate of animal, Btu/h per animal = $6.6W^{0.75}$
W = weight of animal, lb

Conditions in animal rooms must be maintained constant. This may require year-round availability of refrigeration and, in some cases, dual/standby chillers and emergency electrical power for motors and control instrumentation. Storage of critical spare parts is one alternative to installing a standby refrigeration system.

Design Considerations

If the entire animal facility or extensive portions of it are permanently planned for species with similar requirements, the range of

Table 1 Recommended Dry-Bulb Temperatures for Common Laboratory Animals

Animal	Temperature, °F
Mouse, rat, hamster, gerbil, guinea pig	64 to 79
Rabbit	61 to 72
Cat, dog, nonhuman primate	64 to 84
Farm animals and poultry	61 to 81

Source: ILAR (1996). Reprinted with permission.
Note: These ranges permit scientific personnel who will use the facility to select optimum conditions (set points). The ranges do not represent acceptable fluctuation ranges.

Table 2 Heat Generated by Laboratory Animals

Species	Weight, lb	Heat Generation, Btu/h per Normally Active Animal		
		Sensible	Latent	Total
Mouse	0.046	1.11	0.54	1.65
Hamster	0.260	4.02	1.98	6.00
Rat	0.62	7.77	3.83	11.6
Guinea pig	0.90	10.2	5.03	15.2
Rabbit	5.41	39.2	19.3	58.5
Cat	6.61	45.6	22.5	68.1
Nonhuman primate	12.0	71.3	35.1	106.0
Dog	22.7	105.0	56.4	161.0
Dog	50.0	231.0	124.0	355.0

individual adjustments may be reduced. Each animal room or group of rooms serving a common purpose should have separate temperature and humidity controls. The animal facility and human occupancy areas should be conditioned separately. The human areas may use a return air HVAC system and may be shut down on weekends for energy conservation. Separation prevents exposure of personnel to biological agents, allergens, and odors from animal rooms.

Control of air pressure in animal housing and service areas is important to ensure directional airflow. For example, quarantine, isolation, soiled equipment, and biohazard areas should be kept under negative pressure, whereas clean equipment and pathogen-free animal housing areas and research animal laboratories should be kept under positive pressure (ILAR 1996).

Supply air outlets should not cause drafts on research animals. Efficient air distribution for animal rooms is essential; this may be accomplished effectively by supplying air through ceiling outlets and exhausting air at floor level (Hessler and Moreland 1984). Supply and exhaust systems should be sized to minimize noise.

A study by Neil and Larsen (1982) showed that predesign evaluation of a full-size mock-up of the animal room and its HVAC system was a cost-effective way to select a system that distributes air to all areas of the animal-holding room. Wier (1983) describes many typical design problems and their resolutions. Room air distribution should be evaluated using ASHRAE *Standard* 113 procedures to evaluate drafts and temperature gradients.

HVAC ductwork and utility penetrations must present a minimum number of cracks in animal rooms so that all wall and ceiling surfaces can be easily cleaned. Exposed ductwork is not generally recommended; however, if constructed of 316 stainless steel in a fashion to facilitate removal for cleaning, it can provide a cost-effective alternative. Joints around diffusers, grilles, and the like should be sealed. Exhaust air grilles with 1 in. washable or disposable filters are normally used to prevent animal hair and dander from entering the ductwork. Noise from the HVAC system and sound transmission from nearby spaces should be evaluated. Sound control methods such as separate air-handling systems or sound traps should be used as required.

Multiple-cubicle animal rooms enhance the operational flexibility of the animal room (i.e., housing multiple species in the same room, quarantine, and isolation). Each cubicle should be treated as if it were a separate animal room, with air exchange/balance, temperature, and humidity control.

Caging Systems

Animal facilities use a number of different caging systems that can significantly affect the environment within the cage or the total heat load in the room. The purpose of the caging systems is to

- Protect the health and wellbeing of the animals
- Protect support staff from antigens released or shed by the animals
- Minimize exposure of animals to pheromones released by other animals in the space

To provide the appropriate design, the HVAC engineer must be aware of the type of caging system to be used. Some common caging systems include the following:

- Cage boxes made of sheet metal, plastic, or wire mesh, with the space inside the cage open to the room so that the room's macroenvironment is essentially identical to the cage's microenvironment.
- Cage boxes made primarily of plastic, with the top shielded from the room by a filter material to provide some level of isolation from the room. The filter is usually not sealed to the cage, so some open space between the room and the interior of the cage remains. Exchange of air, vapors, particulates, and gases between the room and the cage interior does occur, but the rate of exchange is reduced by the filter. The microenvironment of the interior of the cage is usually different from that of the room.

- Plastic and wire cages that are part of a cage rack assembly, which provides varying degrees of isolation from the room. These usually provide filtered (generally HEPA-filtered) air directly to each individual or shelf of cage boxes. In some cases, both a fan-powered supply and an exhaust unit are used. In other cases, cage units are connected to the facility exhaust system to provide airflow. Facilities with this kind of caging system must be designed to accommodate the heat gain in the space if the exhaust is released in the room. Some heat gain may be excluded if the caging assembly is connected directly to the facility exhaust system. When the facility is used to provide the exhaust by direct connection to the caging assembly, the design must include provisions to control the airflow to ensure that the overall proper airflow and relative static pressure of the room and each cage rack assembly is maintained, especially when caging and rack connections may be changed over time. The temperature and specific humidity within each cage will be higher then the ambient conditions of the room.

ANCILLARY SPACES FOR ANIMAL LABORATORIES

In addition to animal holding rooms, a facility intended to provide for an animal colony generally requires other areas, such as

- **Cage washer:** Usually provided with some temperature control to minimize heat stress for occupants. In addition, specific exhaust hoods and separate exhaust ductwork should be considered for the space and equipment.
- **Feed storage:** Usually provided with temperature and humidity control to protect quality and shelf life of feed.
- **Diagnostic laboratory:** Usually provided with laboratory-quality air conditioning.
- **Treatment laboratory:** Usually provided with laboratory-quality air conditioning.
- **Quarantine spaces:** To separate incoming animals from the remainder of the colony until their health can be evaluated. These rooms are frequently located near the receiving location. Animal-room-quality air conditioning is provided.
- **Surgery suite:** Sterile-quality air conditioning is provided. The suites frequently have provisions to exhaust anesthetic gases.
- **Necropsy laboratory:** Usually provided with laboratory-quality air conditioning and frequently fitted with special exhaust tables or other means of protecting laboratory workers from exposure to chemical preservatives or biological contamination. For high-risk or high-hazard work, Type III biological safety cabinets may be provided.
- **Waste-holding room:** Usually only provided with heating and ventilation, but maintained at negative pressure relative to adjacent areas. When used to store carcasses, a refrigerated storage unit of appropriate size should be provided.

CONTAINMENT LABORATORIES

With the initiation of biomedical research involving recombinant DNA technology, federal guidelines on laboratory safety were published that influence design teams, researchers, and others. Containment describes safe methods for managing hazardous chemicals and infectious agents in laboratories. The three elements of containment are laboratory operational practices and procedures, safety equipment, and facility design. Thus, the HVAC design engineer helps decide two of the three containment elements during the design phase.

In the United States, the U.S. Department of Health and Human Services (DHHS), Centers for Disease Control and Prevention (CDC), and National Institutes of Health (NIH) classify biological laboratories into four levels—Biosafety Levels 1 through 4—listed in DHHS (1999).

Biosafety Level 1

Biosafety Level 1 is suitable for work involving agents of no known hazard or of minimal potential hazard to laboratory personnel and the environment. The laboratory is not required to be separated from the general traffic patterns in the building. Work may be conducted either on an open benchtop or in a chemical fume hood. Special containment equipment is neither required nor generally used. The laboratory can be cleaned easily and contains a sink for washing hands. The federal guidelines for these laboratories contain no specific HVAC requirements, and typical college laboratories are usually acceptable. Many colleges and research institutions require directional airflow from the corridor into the laboratory, chemical fume hoods, and approximately three to four air changes per hour of outside air. Directional airflow from the corridor into the laboratory helps to control odors.

Biosafety Level 2

Biosafety Level 2 is suitable for work involving agents of moderate potential hazard to personnel and the environment. DHHS (1999) contains lists that explain the levels of containment needed for various hazardous agents. Laboratory access is limited when certain work is in progress. The laboratory can be cleaned easily and contains a sink for washing hands. Biological safety cabinets (Class I or II) are used whenever

- Procedures with a high potential for creating infectious aerosols are conducted. These include centrifuging, grinding, blending, vigorous shaking or mixing, sonic disruption, opening containers of infectious materials, inoculating animals intranasally, and harvesting infected tissues or fluids from animals or eggs.
- High concentrations or large volumes of infectious agents are used. Federal guidelines for these laboratories contain minimum facility standards.

At this level of biohazard, most research institutions have a full-time safety officer (or safety committee) who establishes facility standards. The federal guidelines for Biosafety Level 2 contain no specific HVAC requirements; however, typical HVAC design criteria can include the following:

- 100% outside air systems
- 6 to 15 air changes per hour
- Directional airflow into the laboratory rooms
- Site-specified hood face velocity at fume hoods (many institutions specify 80 to 100 fpm)
- An assessment of research equipment heat load in a room.
- Inclusion of biological safety cabinets

Most biomedical research laboratories are designed for Biosafety Level 2. However, the laboratory director must evaluate the risks and determine the correct containment level before design begins.

Biosafety Level 3

Biosafety Level 3 applies to facilities in which work is done with indigenous or exotic agents that may cause serious or potentially lethal disease as a result of exposure by inhalation. The Biosafety Level 3 laboratory uses a physical barrier of two sets of self-closing doors to separate the laboratory work area from areas with unrestricted personnel access. This barrier enhances biological containment to within the laboratory work area.

The ventilation system must be single-pass, nonrecirculating and configured to maintain the laboratory at a negative pressure relative to surrounding areas. Audible alarms and visual monitoring devices are recommended to notify personnel if the laboratory pressure relationship changes from a negative to a positive condition. The user may wish to have alarms reported to a remote constantly monitored location. Gastight dampers are required in the supply and exhaust ductwork to allow decontamination of the laboratory. The ductwork between these dampers and the laboratory must also be gastight. All penetrations of the Biosafety Level 3 laboratory envelope must be sealed for containment and to facilitate gaseous decontamination of the work area.

All procedures involving the manipulation of infectious materials are conducted inside biological safety cabinets. The engineer must ensure that the connection of the cabinets to the exhaust system does not adversely affect the performance of the biological safety cabinets or the exhaust system. Refer to the section on Biological Safety Cabinets for further discussion.

The exhaust air from biological safety cabinets and/or the laboratory work area may require HEPA filtration. The need for filtration should be reviewed with the appropriate safety officers. If required, HEPA filters should be equipped with provisions for bag-in, bag-out filter handling systems and gastight isolation dampers for biological decontamination of the filters.

The engineer should review with the safety officer the need for special exhaust or filtration of exhaust from any scientific equipment located in the Biosafety Level 3 laboratory.

Biosafety Level 4

Biosafety Level 4 is required for work with dangerous and exotic agents that pose a high risk of aerosol-transmitted laboratory infections and life-threatening disease. HVAC systems for these areas will have stringent design requirements that must be determined by the biological safety officer.

SCALE-UP LABORATORIES

Scale-up laboratories are defined differently depending on the nature and volume of work being conducted. For laboratories performing recombinant DNA research, large-scale experiments involve 10 L or more. A chemical or biological laboratory is defined as scale-up when the principal holding vessels are glass or ceramic. When the vessels are constructed primarily of metals, the laboratory is considered a pilot plant, which this chapter does not address. The amount of experimental materials present in scale-up laboratories is generally significantly greater than the amount found in the small-scale laboratory. Experimental equipment is also larger and therefore requires more space; these may include larger chemical fume hoods or reaction cubicles that may be of the walk-in type. Significantly higher laboratory airflow rates are needed to maintain the face velocity of the chemical fume hoods or reaction cubicles, although their size frequently presents problems of airflow uniformity over the entire face area. Walk-in hoods are sometimes entered during an experimental run, so provisions for breathing-quality air stations and other forms of personnel protection should be considered. Environmental containment or the ability to decontaminate the laboratory, the laboratory exhaust airstream, or other effluent may be needed in the event of an upset. Scale-up laboratories may be in operation for sustained periods.

For large walk-in hoods or reaction cubicles, the large volume of exhaust air required and the simultaneous requirement for supply air can result in temperature gradient problems in the space. Local specific ventilation capability is frequently provided within the laboratory space but outside the fume hood or reaction cubicle.

Large hoods, similar to what sometimes were called "California hoods," may also be provided in scale-up laboratories. These hoods are large in volume and height, provide access on multiple sides, and can be customized using standard components. Before beginning any custom hood design, the HVAC engineer, working with the user, should first determine how the hood will be used. Then the HVAC engineer can develop a custom hood design that considers

- What access is required for setup of experimental apparatus
- How the hood is expected to function during experimental runs
- Which doors or sashes should be open during a run
- Safety and ergonomic issues
- What features should be incorporated
- Airflow required to achieve satisfactory containment

Testing and balancing criteria should also be defined early in the design process. Mockups and factory testing of prototypes should be considered to avoid problems with installed hoods.

TEACHING LABORATORIES

Laboratories in academic settings can generally be classified as either those used for instruction or those used for research. Research laboratories vary significantly depending on the work being performed; they generally fit into one of the categories of laboratories described previously.

The design requirements for teaching laboratories also vary based on their function. The designer should become familiar with the specific teaching program, so that a suitable hazard assessment can be made. For example, the requirements for the number and size of fume hoods vary greatly between undergraduate inorganic and graduate organic chemistry teaching laboratories. Unique aspects of teaching laboratories include the need of the instructor to be in visual contact with the students at their work stations and to have ready access to the controls for the fume hood operations and any safety shutoff devices and alarms. Frequently, students have not received extensive safety instruction, so easily understood controls and labeling are necessary. Because the teaching environment depends on verbal communication, sound from the building ventilation system is an important concern.

CLINICAL LABORATORIES

Clinical laboratories are found in hospitals and as stand-alone operations. The work in these laboratories generally consists of handling human specimens (blood, urine, etc.) and using chemical reagents for analysis. Some samples may be infectious; because it is impossible to know which samples may be contaminated, good work practices require that all be handled as biohazardous materials. The primary protection of the staff at clinical laboratories depends on the techniques and laboratory equipment (e.g., biological safety cabinets) used to control aerosols, spills, or other inadvertent releases of samples and reagents. People outside the laboratory must also be protected.

The building HVAC system can provide additional protection with suitable exhaust, ventilation, and filtration. The HVAC engineer is responsible for providing an HVAC system that meets the biological and chemical safety requirements. The engineer should consult with appropriate senior staff and safety professionals to ascertain what potentially hazardous chemical or biohazardous conditions will be in the facility and then provide suitable engineering controls to minimize risks to staff and the community. Appropriate laboratory staff and the design engineer should consider using biological safety cabinets, chemical fume hoods, and other specific exhaust systems.

RADIOCHEMISTRY LABORATORIES

In the United States, laboratories located in Department of Energy (DOE) facilities are governed by DOE regulations. All other laboratories using radioactive materials are governed by the Nuclear Regulatory Commission (NRC), state, and local regulations. Other agencies may be responsible for the regulation of other toxic and carcinogenic materials present in the facility. Laboratory containment equipment for nuclear processing facilities are treated as primary, secondary, or tertiary containment zones, depending on the level of radioactivity anticipated for the area and the materials to be handled. Chapter 26 has additional information on nuclear laboratories.

OPERATION AND MAINTENANCE

During long-term research studies, laboratories may need to maintain design performance conditions with no interruptions for long periods. Even when research needs are not so demanding, systems that maintain air balance, temperature, and humidity in laboratories must be highly reliable, with a minimal amount of downtime. The designer should work with operation and maintenance personnel as well as users early in the design of systems to gain their input and agreement.

System components must be of adequate quality to achieve reliable HVAC operation, and they should be reasonably accessible for maintenance. Laboratory work surfaces should be protected from possible leakage of coils, pipes, and humidifiers. Changeout of supply and exhaust filters should require minimum downtime.

Centralized monitoring of laboratory variables (e.g., pressure differentials, face velocity of fume hoods, supply flows, and exhaust flows) is useful for predictive maintenance of equipment and for ensuring safe conditions. For their safety, laboratory users should be instructed in the proper use of laboratory fume hoods, safety cabinets, ventilated enclosures, and local ventilation devices. They should be trained to understand the operation of the devices and the indicators and alarms that show whether they are safe to operate. Users should request periodic testing of the devices to ensure that they and the connected ventilation systems are operating properly.

Personnel who know the nature of the contaminants in a particular laboratory should be responsible for decontamination of equipment and ductwork before they are turned over to maintenance personnel for work.

Maintenance personnel should be trained to keep laboratory systems in good operating order and should understand the critical safety requirements of those systems. Preventive maintenance of equipment and periodic checks of air balance should be scheduled. High-maintenance items should be placed outside the actual laboratory (in service corridors or interstitial space) to reduce disruption of laboratory operations and exposure of the maintenance staff to laboratory hazards. Maintenance personnel must be aware of and trained in procedures for maintaining good indoor air quality (IAQ) in laboratories. Many IAQ problems have been traced to poor maintenance due to poor accessibility (Woods et al. 1987).

ENERGY

Because of the nature of the functions they support, laboratory HVAC systems consume large amounts of energy (high flow rates; high static pressure filtration; critical cooling, heating, and humidification). Efforts to reduce energy use must not compromise standards established by safety officers. Typically, HVAC systems supporting laboratories and animal areas use 100% outside air and operate continuously. All HVAC systems serving laboratories can benefit from energy reduction techniques that are either an integral part of the original design or added later. Energy reduction techniques should be analyzed in terms of both appropriateness to the facility and economic payback.

Energy-efficient design is an iterative process that begins with establishing communication among all members of the design team. Each design discipline has an effect on the energy load. On a macro scale, the flexibility of the architectural design can allow such features as a modular laboratory size. On a micro scale, the choice of a lighting system can affect sensible heat gain and transformer sizing, for example. Energy-efficient designs account for the potential variability of a minimized load and match the load with flexible electrical and mechanical systems. This systems approach is fundamental to an integrated system design.

The HVAC engineer must understand and respond to the scientific requirements of the facility. Research requirements typically include continuous control of temperature, humidity, relative static pressure, and air quality. Energy reduction systems must maintain required environmental conditions during both occupied and unoccupied modes.

Energy Efficiency

Energy can be used more efficiently in laboratories by reducing exhaust air requirements. One way to achieve this is to use variable-volume control of exhaust air through the fume hoods to reduce exhaust airflow when the fume hood sash is not fully open. Any airflow control must be integrated with the laboratory control system, described in the section on Control, and must not jeopardize the safety and function of the laboratory.

Another energy-efficiency method uses night setback controls when the laboratory is unoccupied to reduce exhaust volume to one-quarter to one-half the minimum required when the laboratory is occupied. Timing devices, sensors, manual override, or a combination of these can be used to set back the controls at night. If this strategy is a possibility, the safety and function of the laboratory must be considered, and appropriate safety officers should be consulted.

Also, fume sash configurations that limit the opening to less than the full open condition should be considered.

Energy Recovery

Energy can often be recovered economically from the exhaust airstream in laboratory buildings with large quantities of exhaust air. Many energy recovery systems are available, including rotary air-to-air energy exchangers or heat wheels, coil energy recovery loops (runaround cycle), twin tower enthalpy recovery loops, heat pipe heat exchangers, fixed-plate heat exchangers, thermosiphon heat exchangers, and direct evaporative cooling. Some of these technologies can be combined with indirect evaporative cooling for further energy recovery. See Chapter 44 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment* for more information.

Concerns about the use of energy recovery devices in laboratory HVAC systems include (1) the potential for cross-contamination of chemical and biological materials from exhaust air to the intake airstream, and (2) the potential for corrosion and fouling of devices located in the exhaust airstream. NFPA *Standard* 45 specifically prohibits the use of latent heat recovery devices in fume hood exhaust systems.

Energy recovery is also possible for hydronic systems associated with HVAC. Rejected heat from centrifugal chillers can be used to produce low-temperature reheat water. Potential also exists in plumbing systems, where waste heat from washing operations can be recovered to heat makeup water.

COMMISSIONING

In addition to HVAC systems, electrical systems and chemical handling and storage areas must be commissioned. Training of technicians, scientists, and maintenance personnel is a critical aspect of the commissioning process. Users must understand the systems and their operation.

It should be determined early in the design process whether any laboratory systems must comply with Food and Drug Administration (FDA) regulations because these systems have additional design and commissioning requirements. Commissioning is defined in Chapter 42, and the process is outlined in ASHRAE *Guideline* 1. Laboratory commissioning is more demanding than that described in ASHRAE *Guideline* 1 because areas must be considered that are not associated with the normal office complex. Requirements for commissioning should be clearly understood by all participants, including the contractors and the owner's personnel. Roles and responsibilities should be defined, and responsibilities for documenting results should be established.

Laboratory commissioning starts with the intended use of the laboratory and should include development of a commissioning plan, as outlined in ASHRAE *Guideline* 1. The validation of individual components should come first; after individual components are successfully validated, the entire system should be evaluated. This requires verification and documentation that the design meets applicable codes and standards and that it has been constructed in accordance with the design intent. Before general commissioning begins, the following data must be obtained:

- Complete set of the laboratory utility drawings
- Definition of the use of the laboratory and an understanding of the work being performed
- Equipment requirements
- All test results
- Understanding of the intent of the system operation

For HVAC system commissioning, the following should be verified and documented:

- Fume hood design face velocities have been met.
- Manufacturer's requirements for airflow for biological safety cabinets and laminar flow clean benches have been met.
- Exhaust system configuration, damper locations, and performance characteristics, including any required emission equipment, are correct.
- Control system operates as specified. Controls include fume hood alarm; miscellaneous safety alarm systems; fume hood and other exhaust airflow regulation; laboratory pressurization control system; laboratory temperature control system; and main ventilation unit controls for supply, exhaust, and heat recovery systems. Control system performance verification should include speed of response, accuracy, repeatability, turndown, and stability.
- Desired laboratory pressurization relationships are maintained throughout the laboratory, including entrances, adjoining areas, air locks, interior rooms, and hallways. Balancing terminal devices within 10% of design requirements will not provide adequate results. Additionally, internal pressure relationships can be affected by airflow around the building itself. See Chapter 16 of the 2005 *ASHRAE Handbook—Fundamentals* for more information.
- Fume hood containment performance is within specification. ASHRAE *Standard* 110 provides criteria for this evaluation.
- Dynamic response of the laboratory's control system is satisfactory. One method of testing the control system is to open and shut laboratory doors during fume hood performance testing.
- System fault tree and failure modes are as specified.
- Standby electrical power systems function properly.
- Design noise criterion (NC) levels of occupied spaces have been met.

ECONOMICS

In laboratories, HVAC systems make up a significant part (often 30 to 50%) of the overall construction budget. The design criteria and system requirements must be reconciled with the budget allotment for HVAC early in the planning stages and continually throughout the design stages to ensure that the project remains within budget.

Every project must be evaluated on both its technical features and its economics. The following common economic terms are discussed in Chapter 36 and defined here as follows:

Initial cost: Costs to design, install, and test an HVAC system such that it is fully operational and suitable for use.

Operating cost: Cost to operate a system (including energy, maintenance, and component replacements) such that the total system can reach the end of its normal useful life.

Life-cycle cost: Cost related to the total cost over the life of the HVAC system, including initial capital cost, considering the time value of money.

Mechanical and electrical costs related to HVAC systems are commonly assigned a depreciation life based on current tax policies. This depreciation life may be different from the projected functional life of the equipment, which is influenced by the quality of the

system components and of the maintenance they receive. Some portions of the system, such as ductwork, could last the full life of the building. Other components, such as air-handling units, may have a useful life of 15 to 30 years, depending on their original quality and ongoing maintenance efforts. Estimated service life of equipment is listed in Chapter 36.

Engineering economics can be used to evaluate life-cycle costs of configuration (utility corridor versus interstitial space), systems, and major equipment. The user or owner makes a business decision concerning the quality and reliability of the system and its ongoing operating costs. The HVAC engineer may be asked to provide an objective analysis of energy, maintenance, and construction costs, so that an appropriate life-cycle cost analysis can be made. Other considerations that may be appropriate include economic influences related to the long-term use of energy and governmental laws and regulations.

Many technical considerations and the great variety of equipment available influence the design of HVAC systems. Factors affecting design must be well understood to ensure appropriate comparisons between various systems and to determine the impact on either first or operating costs.

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CHAPTER 15

ENGINE TEST FACILITIES

INDUSTRIAL testing of turbine and internal combustion engines is performed in enclosed test spaces to control noise and isolate the test for safety or security. These spaces are ventilated or conditioned to control the facility environment and fumes. Isolated engines are tested in test cells; engines inside automobiles are tested on chassis dynamometers. The ventilation and safety principles for test cells also apply when large open areas in the plant are used for production testing and emissions measurements.

Enclosed test cells are normally found in research or emissions test facilities. Test cells may require instruments to measure cooling system water flow and temperature; exhaust gas flow, temperature, and emission concentrations; fuel flow; power output; and combustion air volume and temperature. Changes in the temperature and humidity of the test cell affect these measurements. Accurate control of the testing environment is becoming more critical. For example, the U.S. Environmental Protection Agency requires tests to demonstrate control of automobile contaminants in both hot and cold environments.

Air conditioning and ventilation of test cells must (1) supply and exhaust proper quantities of air to remove heat and control temperature; (2) exhaust sufficient air at proper locations to prevent buildup of combustible vapors; (3) supply and modulate large quantities of air to meet changing conditions; (4) remove exhaust fumes; (5) supply combustion air; (6) prevent noise transmission through the system; (7) provide for human comfort and safety during setup, testing, and tear-down; and (8) treat the exhaust effluent. Supply and exhaust systems for test cells may be unitary, central, or a combination of the two. Mechanical exhaust is necessary in all cases.

ENGINE HEAT RELEASE

The special air-conditioning requirements of an engine test facility stem from burning the fuel used to run the engine. For internal combustion engines at full load, 10% of the total heat content of the fuel is radiated and convected into the room or test cell atmosphere, and 90% is fairly evenly divided between the shaft output (work), exhaust gas heating, and heating of the jacket cooling water.

Air-cooled engines create a forced convection load on the test space equal to the jacket water heat that it replaces. For turbine engines, the exhaust gas carries double the heat of the internal combustion engine exhaust and there is no jacket water to heat. The engine manufacturer can provide a more precise analysis of heat release characteristics at various speeds and power outputs.

Test facilities use dynamometers to determine the power supplied by the engine shaft. The dynamometer converts shaft work into heat that must be accounted for by a cooling system or as heat load into the space. Often, shaft work is converted into electricity through a generator and the electric power is dissipated by a resistance load bank or sold to the local utility. Inefficiencies of the various pieces of equipment add to the load of the space in which they are located.

The preparation of this chapter is assigned to TC 9.2, Industrial Air Conditioning.

Heat released into the jacket water must also be removed. If a closely connected radiator is used, the heat load is added to the room load. Many test facilities include a heat exchanger and a secondary cooling circuit transfers the heat to a cooling tower. Some engines require an oil cooler separate from the jacket water. Whichever system is used, the cooling water flow, temperature, and pressure are usually monitored as part of the test operation and heat from these sources needs to be accommodated by the facility's air conditioning.

Exhaust systems present several challenges to engine test cell design. Exhaust gases can exit the engine at 1500°F or higher. Commonly, the exhaust gas is augmented by inserting the exhaust pipe into a larger-bore exhaust system (laboratory fixed system), which draws room air into the exhaust to both cool the gas and ventilate the test cell. Both the exhausted room air and combustion air must be supplied to the room from the HVAC or from outside.

Radiation and convection from exhaust pipes, catalytic converter, muffler, etc., also add to the load. In most cases, the test cell's HVAC system should account for an engine that can fully load the dynamometer, and have capacity control for operation at partial and no load.

Large gas turbine engines have unique noise and airflow requirements; therefore, they usually are provided with dedicated test cells. Small gas turbines can often be tested in a regular engine test cell with minor modifications.

ENGINE EXHAUST

Engine exhaust systems remove combustible products, unburned fuel vapors, and water vapor. Flow loads and operating pressure need to be established for design of the supporting HVAC.

Flow loads are calculated based on the number of engines, the engine sizes and loads, and use factors or diversity.

Operating pressure is the engine discharge pressure at the connection to the exhaust. Systems may operate at positive pressure using available engine tail-pipe pressure to force the flow of gas, or at negative pressure with mechanically induced flow.

The simplest way to induce engine exhaust from a test cell is to size the exhaust pipe to minimize variations in pressure on the engine and to connect it directly to the outside (Figure 1A). Exhausts directly connected to the outside are subject to wind currents and air pressure, however, and can be hazardous because of positive pressure in the system.

Mechanical engine exhausts are either unitary or central. A **unitary exhaust** (Figure 1B) serves only one test cell, and can be closely regulated to match the engine's operation. A **central exhaust** (Figure 1D) serves multiple test cells with one or more exhaust fans and a duct system with branch connections to the individual test cells. Relief of a possible explosion in the ductwork should be considered.

Engine exhaust pressures fluctuate with changes in engine load and speed. Central exhausts should be designed to minimize effects of load variations in individual test cells on the system. Engine characteristics and diversity of operation determine the maximum airflow to be handled. Dampers and pressure regulators may be required to keep pressures within test tolerances.

Fig. 1   Engine Exhaust Systems

Fig. 2   Engine Test Cell Showing Direct Engine Exhaust: Unitary Ventilation System
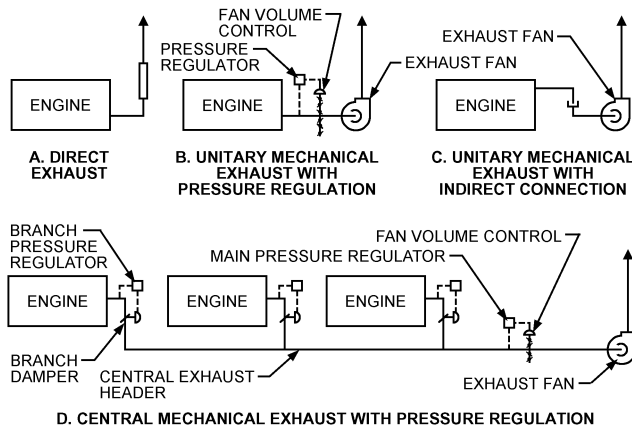
An indirect connection between the engine exhaust pipe and mechanical exhaust gas removal (Figure 1C) eliminates variation in back pressure and augments exhaust gas flow by inducing room air into the exhaust stream. In this system the engine exhaust pipe terminates by being centered and inserted about 3 in. into the augmentation pipe, which is at least 1 in. larger in diameter. The induced room air is mixed with the exhaust gases, yielding a much cooler exhaust flow. However, the potential for increased corrosion in a cooler exhaust must be considered when selecting construction materials. The engine muffler should be located upstream of the augmentation connection to control noise. The indirect connection should be considered a potential point of ignition if the exhaust is fuel rich and the tail pipe reaches temperatures above 700°F.

Exhaust pipes and mufflers run very hot. A ventilated heat shield or a water-jacketed pipe reduces cell heat load, and some exhausts are equipped with direct water injection. Thermal expansion, stress, and pressure fluctuations must also be considered in the design of the exhaust fan and ducting. The equipment must be adequately supported and anchored to relieve the thermal expansion.

Exhaust systems for chassis dynamometer installations must capture high-velocity exhaust from the tail pipe to prevent fume buildup in the room. An exhaust flow rate of 700 cfm has been used effectively for automobiles at a simulated speed of 65 mph.

Engine exhaust should discharge through a stack extending above the roof to an elevation sufficient to allow the fumes to clear the building. Chapter 44 has further details about exhaust stacks. Codes or air emission standards may require that exhaust gases be cleaned before being discharged to atmosphere.

INTERNAL COMBUSTION ENGINE TEST CELLS

Test Cell Exhaust

Ventilation for test cells is based on exhaust requirements for (1) removal of heat generated by the engine, (2) emergency purging (removal of fumes after a fuel spill), and (3) continuous cell scavenging during nonoperating periods. Heat is transferred to the test cell by convection and radiation from all of the heated surfaces, such as the engine and exhaust system. At a standard air density of $\rho = 0.075$ lb/ft^3 and specific heat $c_p = 0.24$ Btu/lb·°F,

$$Q = \frac{q}{60\rho c_p(t_e - t_s)} = \frac{q}{1.08(t_e - t_s)}$$

where

Q = airflow, cfm
q = engine heat release, Btu/h
t_e = temperature of exhaust air, °F
t_s = temperature of supply air, °F
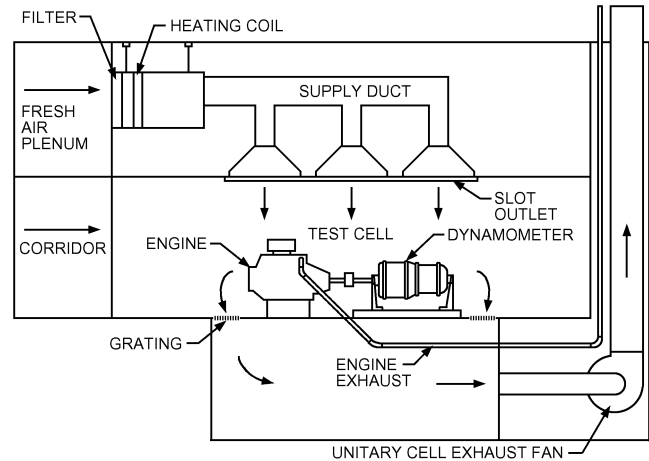
The constant (1.08) should be corrected for other temperatures and pressures.

Heat radiated from the engine, dynamometer, and exhaust piping warms surrounding surfaces, which release heat to the air by convection. The value for $(t_e - t_s)$ in the equation cannot be arbitrarily set when a portion of q is radiated heat. The section on Engine Heat Release discusses other factors required to determine the overall q.

Vapor Removal. The exhaust should remove vapors as quickly as possible. Emergency purging, often 10 cfm per square foot of floor area, should be controlled by a manual overriding switch for each test cell. In case of fire, provisions need to be made to shut down all equipment, close fire dampers at all openings, and shut off the fuel-flow solenoid valves.

Cell Scavenging. Exhaust air is the minimum amount of air required to keep combustible vapors from fuel leaks from accumulating. In general, 2 cfm per square foot of floor area is sufficient. Because gasoline vapors are heavier than air, exhaust grilles should be low even when an overhead duct is used. Exhausting close to the engine minimizes the convective heat that escapes into the cell.

In some installations, all air is exhausted through a floor grating surrounding the engine bed plate and into a cubicle or duct below. In this arrangement, slots in the ceiling over the engine supply a curtain of air to remove the heat. This scheme is particularly suitable for a central exhaust (Figure 2). Water sprays in the underfloor exhaust lessen the danger of fire or explosion in case of fuel spills.

Trenches and pits should be avoided in test cells. If they exist, as in most chassis dynamometer rooms, they should be mechanically exhausted at all times. Long trenches may require multiple exhaust takeoffs. The exhaust should sweep the entire area, leaving no dead air spaces. Because of fuel spills and vapor accumulation, suspended ceilings or basements should not be located directly below the engine test cell. If such spaces exist, they should be ventilated continuously and have no fuel lines running through them.

Table 1 lists exhaust quantities used in current practice; the exhaust should be calculated for each test cell on the basis of heat to be removed, evaporation of possible fuel spills, and the minimum ventilation needed during downtime.

TEST CELL SUPPLY

The air supply to a test cell should be balanced to yield a slightly negative pressure. Test cell air should not be recirculated. Air taken from nontest areas can be used if good ventilation practices are

Table 1 Exhaust Quantities for Test Cells

	Minimum Exhaust Rates per Square Foot of Floor Area	
	cfm	ach[a]
Engine testing—cell operating	10	60[b]
Cell idle	2	12
Trenches[c] and pits	10	—
Accessory testing	4	24
Control rooms and corridors	1	6

[a] Air changes per hour, based on cell height of 10 ft.
[b] For chassis dynamometer rooms, this quantity is usually set by test requirements.
[c] For large trenches, use 100 fpm across the cross-sectional area of the trench.

followed, such as using air that is free of unacceptable contaminants, is sufficient for temperature control, and can maintain the proper test cell pressure.

Ventilation air should keep heat released from the engine away from cell occupants. Slot outlets with automatic dampers to maintain a constant discharge velocity have been used with variable-volume systems.

A variation of systems C and D in Figure 3 includes a separate air supply sized for the minimum (downtime) ventilation rate and for a cooling coil with room thermostat to regulate the coil to control the temperature in the cell. This system is useful in installations where much time is devoted to the setup and preparation of tests, or where constant temperature is required for complicated or sensitive instrumentation. Except for production and endurance testing, the actual engine operating time in test cells may be surprisingly low. The average test cell is used approximately 15 to 20% of the time.

Air should be filtered to remove particulates and insects. The degree of filtration is determined by the type of tests. Facilities in relatively unpolluted areas sometimes use unfiltered outdoor air.

Heating coils are needed to temper supply air if there is danger of freezing equipment or if low temperatures adversely affect tests. For low-temperature applications, a desiccant wheel with pre- and post-cooling may be needed with appropriate environmentally friendly refrigerants.

GAS-TURBINE TEST CELLS

Large gas-turbine test cells must handle large quantities of air required by the turbine, attenuate the noise generated, and operate safely with a large flow of fuel. These cells are unitary and use the turbine to draw in untreated air and exhaust it through noise attenuators.

Small gas turbine engines can generally be tested in a conventional test cell with relatively minor modifications. The test-cell ventilation air supply and exhausts are sized for turbine-generated heat as for a conventional engine. The combustion air supply for the turbine is considerable; it may be drawn from the cell, from outdoors, or through separate conditioning units that handle only combustion air.

Exhaust quantities are higher than from internal combustion engines and are usually ducted directly to the outdoors through muffling devices that provide little restriction to airflow. Exhaust air may be water-cooled, as temperature may exceed 1300°F.

CHASSIS DYNAMOMETER ROOMS

A chassis dynamometer (Figure 4) simulates road driving and acceleration conditions. The vehicle's drive wheels rest on a large roll, which drives the dynamometer. Air quantities, which are calibrated to correspond to air velocity at a particular road speed, flow across the front of the vehicle for radiator cooling and to approximate the effects of air speed on the body of the vehicle. Additional refinements may vary air temperature within prescribed limits from
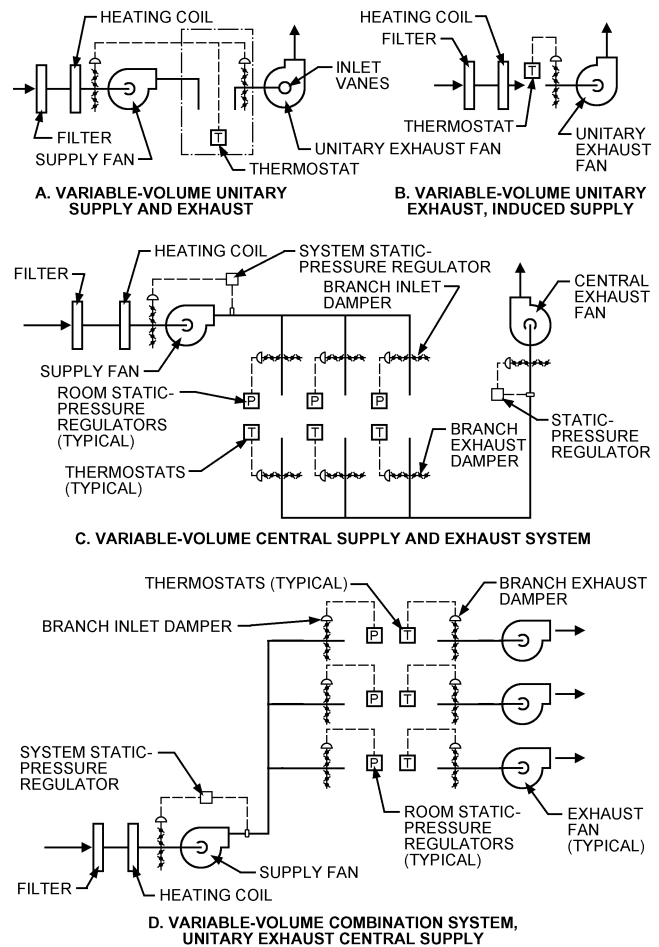
Fig. 3 Heat Removal Ventilation Systems
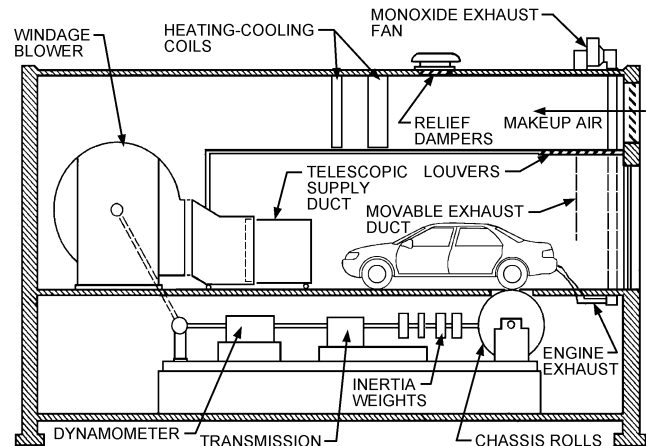
Fig. 4 Chassis Dynamometer Room

−40 to 130°F, control relative humidity, and/or add shakers to simulate road conditions. Air is usually introduced through an area approximating the frontal area of the vehicle. A duct with a return grille at the rear of the vehicle may be lowered so that air remains near the floor rather than cycling through a ceiling return air grille. Air is recirculated to air-handling equipment above the ceiling.

Chassis dynamometers are also installed in

• Cold rooms, where temperatures may be as low as −100°F

- Altitude chambers, where elevations up to 12,000 ft can be simulated
- Noise chambers for sound evaluation
- Electromagnetic cells for evaluation of electrical components
- Environmental chambers
- Full-sized wind tunnels with throat areas much larger than the cross-sectional area of the vehicle. Combustion air is drawn directly from the room, but the engine exhaust must be installed in a way that will preserve the low temperature and humidity.

A temperature soak space is often placed near chassis dynamometer rooms having a controlled temperature. This space is used to cool or heat automobiles scheduled to enter the room. Generally, 18 to 24 h is required before the temperature of the vehicle stabilizes to the temperature of the room. The soak space and the temperature-controlled room are often isolated from the rest of the facility, with entry and egress through an air lock.

VENTILATION

Constant-volume systems with variable supply temperatures can be used; however, variable-volume, variable-temperature systems are usually selected. Ventilation is generally controlled on the exhaust side (see Figure 3). Unitary variable-volume systems (Figure 3A) use an individual exhaust fan and makeup air supply for each cell. Supply and exhaust fans are interlocked, and their operation is coordinated with the engine, usually by sensing the temperature of the cell. Some systems have exhaust only, with supply induced directly from outside (Figure 3B). The volume is varied by changing fan speed or damper position.

Ventilation with central supply fans, central exhaust fans, or both (Figure 3C) regulate air quantities by test cell temperature control of individual dampers or by two-position switches actuated by dynamometer operations. Air balance is maintained by static pressure regulation in the cell. Constant pressure in the supply duct is obtained by controlling supply fan inlet vanes, modulating dampers, or varying fan speed.

In systems with individual exhaust fans and central supply air, exhaust is controlled by cell temperature or a two-position switch actuated by dynamometer operation. The central supply system is controlled by a static pressure device in the cell to maintain room pressure (Figure 3D). Variable-volume exhaust airflow should not drop below minimum requirements. Exhaust requirements should override cell temperature requirements; thus, reheat may be needed.

Ventilation should be interlocked with fire protection to shut down the supply to and exhaust from the cell in case of fire. Exhaust fans should be nonsparking, and makeup air should be tempered.

COMBUSTION AIR SUPPLY

Combustion air is usually drawn from the test cell or introduced directly from the outdoors. Separate dedicated units can be used if combustion air must be closely regulated and conditioning of the entire test cell is impractical. These units filter, heat, and cool the supply air and regulate its humidity and pressure; they usually pro-

Table 2   Typical Noise Levels in Test Cells

Type and Size of Engine	Sound Level 3 ft from Engine, dBA			
	63 Hz	124 Hz	500 Hz	2000 Hz
Diesel				
Full load	105	107	98	99
Part load	70	84	56	49
Gasoline engine, 440 in³ at 5000 rpm				
Full load	107	108	104	104
Part load	75	—	—	—
Rotary engine, 100 hp				
Full load	90	90	83.5	86
Part load	79	78	75	72

vide air directly to the engine air intake. Combustion air systems may be central units or portable packaged units.

COOLING WATER SYSTEMS

Dynamometers absorb and measure the useful output of an engine or its components. In a water-cooled dynamometer, engine work is converted to heat, which is absorbed by circulating water. Electrical dynamometers convert engine work to electrical energy, which can be used or dissipated as heat in resistance grids or load banks or sold to the local utility. Grids should be located outdoors or adequately ventilated.

Heat loss from electric dynamometers is approximately 8% of the measured output, plus a constant load of about 5 kW for auxiliaries in the cell. Recirculating water absorbs heat from the engine jacket water, oil coolers, and water cooled dynamometers through circulating pumps, cooling towers, or atmospheric coolers and hot- and cold-well collecting tanks.

NOISE

Noise generated by internal combustion engines and gas turbines must be considered in the design of a test cell air-handling system. Part of the engine noise is discharged through the tail pipe. If possible, internal mufflers should be installed to attenuate this noise at its source. Any ventilation ducts or pipe trenches that penetrate the cells must be insulated against sound transmission to other areas or to the outdoors. Attenuation equivalent to that provided by the cell structure should be applied to duct penetrations. Table 2 lists typical noise levels in test cells during engine operations.

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CHAPTER 16

CLEAN SPACES

DESIGN of clean spaces or cleanrooms covers much more than traditional temperature and humidity control. Other factors may include control of particle, microbial, electrostatic discharge (ESD), molecular, and gaseous contamination; airflow pattern control; pressurization; sound and vibration control; industrial engineering aspects; and manufacturing equipment layout. The objective of good cleanroom design is to control these variables while maintaining reasonable installation and operating costs.

TERMINOLOGY

Acceptance criteria. Upper and lower limits of a pharmaceutical critical parameter (in this case, the room environment). If these limits are exceeded, the pharmaceutical product may be considered adulterated.

Air lock. A small transitional room between two rooms of different cleanliness and air pressure. Doors at both ends of the transitional room should be programmed to avoid having both open simultaneously, to minimize direct air contact (cross contamination) of the two rooms. Time relay between the doors is required.

As-built cleanroom. A cleanroom that is complete, with all services connected and functional, but without production equipment, materials, or personnel in the room.

Aseptic space. A space controlled such that bacterial growth is contained within acceptable limits. This is not a sterile space, in which absolutely no life exists.

At-rest cleanroom. A cleanroom that is complete with production equipment and materials and is operating, but without personnel in the room.

CFU (colony-forming unit). A measure of bacteria present in a pharmaceutical processing room, measured by sampling as part of performance qualification.

Challenge. An airborne dispersion of particles of known sizes and concentration used to test filter integrity and efficiency.

Cleanroom. A specially constructed enclosed area with environmental control of particulates, temperature, humidity, air pressure, air pressure flow patterns, air motion, vibration, noise, viable organisms, and lighting.

Clean space. A defined area in which particle concentration and environmental conditions are controlled at or below specified limits.

Contamination. Any unwanted material, substance, or energy.

Conventional-flow cleanroom. A cleanroom with nonunidirectional or mixed airflow patterns and velocities.

Critical parameter. A room variable (e.g., temperature, humidity, air changes, room pressure, particulates, viable organisms) that, by law or per pharmaceutical product development data, affects product strength, identity, safety, purity, or quality (SISPQ).

Critical surface. The surface of the work part to be protected from particulate contamination.

Design conditions. The environmental conditions for which the clean space is designed.

DOP. Dioctyl phthalate, an aerosol formerly used for testing efficiency and integrity of HEPA filters.

ESD. Electrostatic discharge.

E.U. European Union guidelines for GMP pharmaceutical manufacturing.

Exfiltration. Air leakage from a room through cracks in doors and pass-throughs or through material transfer openings, etc., because of differences in space pressures.

FDA. U.S. Food and Drug Administration.

First air. Air that issues directly from the HEPA filter before it passes over any work location.

FS 209. A former U.S. *Federal Standard* (canceled in November 2001) that specified airborne particulate cleanliness classes in cleanrooms and clean zones. ISO (International Organization for Standardization) *Standard* 14644-1 is a comparable international standard for cleanrooms. Table 1 and Figure 1 compare and summarize the Federal and ISO standard classes.

GMP. Good manufacturing practice, as defined by *Code of Federal Regulations* (CFR) 21CFR210, 211 (also, cGMP = current GMP).

High-efficiency particulate air (HEPA) filter. A filter with an efficiency over 99.97% of 0.3 μm particles.

LIVE GRAPH
Click here to view
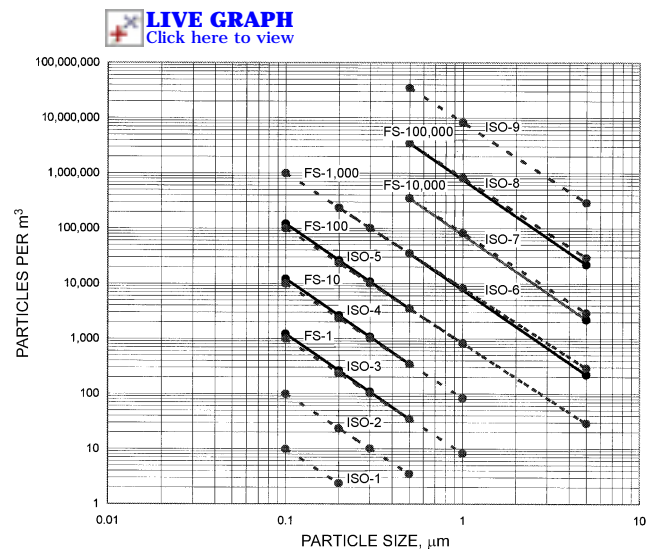
Fig. 1   Air Cleanliness Classifications by U.S. *Federal Standard* 209 and ISO 14644-1

The preparation of this chapter is assigned to TC 9.11, Clean Space.

Table 1   Comparison of Airborne Particle Concentration Limits from FS 209 and ISO/FDIS 14644-1

FS 209 Class	ISO 14644 Class	0.1 µm		0.2 µm		0.3 µm		0.5 µm		1.0 µm		5.0 µm	
		FS 209	ISO 14644	FS 209	ISO 14644	FS 209	ISO 14644	FS 209	ISO 14644	FS 209	ISO 14644	FS 209	ISO 14644
		Particles per		Particles per		Particles per		Particles per		Particles per		Particles per	
		ft³	m³	ft³	m³	ft³	m³	ft³	m³	ft³	m³	ft³	m³
	1		10		2								
	2		100		24		10		4				
1	3	35	1000	7.5	237	3	102	1	35		8		
10	4	350	10,000	75	2370	30	1020	10	352		83		
100	5		100,000	750	23,700	300	10,000	100	3520		832		29
1000	6		1,000,000		237,000		102,000	1000	35,200		8320	7	293
10,000	7							10,000	352,000		83,200	65	2930
100,000	8							100,000	3,520,000		832,000	700	29,300
	9								35,200,000		8,320,000		293,000

Note: Values shown are the concentration limits for particles equal to and larger than the sizes shown.

$C_n = N(0.5/D)^{2.2}$ where C_n = concentration limits in particles/ft³, N = FS 209 class, and D = particle diameter in µm

$C_n = 10^N(0.1/D)^{2.08}$ where C_n = concentration limits in particles/m³, N = ISO class, and D = particle diameter in µm

Table 2   Matrix of ISO Documents to IEST Recommended Practices (RPs)

ISO	IEST RP
14644-1	1, 6
14644-2	1, 6, 7, 34
14644-3	1, 7, 21, 34
14644-4	1, 7, 12, 21, 22, 24, 33
14644-5	3, 4, 5, 18, 20, 22, 26, 27
14644-6	11
14644-7	2, 6, 12, 22, 26, 28, 34
14644-8	16, 31, 35
14644-9	23, 27

IEST. Institute of Environmental Sciences and Technology. For comparison of IEST recommended practices and ISO documents, see Table 2.

Infiltration. Uncontrolled air that exfiltrates from spaces surrounding the cleaner space.

ISPE. International Society for Pharmaceutical Engineering.

ISO. International Organization for Standardization. For comparison of ISO documents and IEST recommended practices, see Table 2.

Laminar flow. See Unidirectional flow.

Leakage. See Exfiltration.

Makeup air. Air introduced to the air system for ventilation, pressurization, and replacement of exhaust air.

Minienvironment/Isolator. A barrier, enclosure, or glove box that isolates products from production workers and other contamination sources.

Monodispersed particles. An aerosol with a narrow band of particle sizes, generally used for challenging and rating HEPA and UPLA air filters.

Nonunidirectional flow workstation. A workstation without uniform airflow patterns and velocities.

Operational cleanroom. A cleanroom in normal operation with all specified services, production equipment, materials, and personnel present and performing their normal work functions.

Oral product. A pharmaceutical product to be taken by mouth by the patient. They are usually not manufactured in aseptic spaces.

PAO. Polyalphaolefin, a substitute for DOP in testing HEPA filters.

Parenteral product. A pharmaceutical product to be injected into the patient. Parenterals are manufactured under aseptic conditions or are terminally sterilized to destroy bacteria and meet aseptic requirements.

Particle concentration. The number of individual particles per unit volume of air.

Particle size. The apparent maximum linear dimension of a particle in the plane of observation.

Polydispersed particles. An aerosol with a broad band of particle sizes, generally used to leak-test filters and filter framing systems.

Qualification. Formal commissioning and operating of a system through established installation, operational, and performance qualification procedures (with approvals).

Qualification protocol. A written description of activities necessary to qualify a pharmaceutical facility, with required approval signatures.

Room classification. Room air quality class (Figure 1, Table 1).

SOP. Standard operating procedure.

Topical product. A pharmaceutical product to be applied to the skin or soft tissue as a liquid, cream, or ointment, which therefore does not need to be aseptic. Sterile ophthalmic products, though, are usually manufactured aseptically.

ULPA (ultralow-penetration air) filter. A filter with a minimum of 99.999% efficiency at 0.12 µm particle size.

Unidirectional flow. Formerly called laminar flow. Air flowing at constant and uniform velocity in the same direction.

Workstation. An open or enclosed work surface with direct air supply.

CLEAN SPACES AND CLEANROOM APPLICATIONS

Use of clean space environments in manufacturing, packaging, and research continues to grow as technology advances and the need for cleaner work environments increases. The following major industries use clean spaces for their products:

Pharmaceuticals/Biotechnology. Preparation of pharmaceutical, biological, and medical products requires clean spaces to control viable (living) particles that would produce undesirable bacterial growth and other contaminants.

Microelectronics/Semiconductor. Advances in semiconductor microelectronics drive cleanroom design. Semiconductor facilities are a significant percentage of all cleanrooms in operation in the United States, with most newer semiconductor cleanrooms being ISO 14644-1 Class 5 or cleaner.

Aerospace. Cleanrooms were first developed for aerospace applications to manufacture and assemble satellites, missiles, and aerospace electronics. Most applications involve large-volume spaces with cleanliness levels of ISO 14644-1 Class 8 or cleaner.

Miscellaneous Applications. Cleanrooms are also used in aseptic food processing and packaging; manufacture of artificial limbs

and joints; automotive paint booths; crystal; laser/optic industries; and advanced materials research.

Hospital operating rooms may be classified as cleanrooms, but their primary function is to limit particular types of contamination rather than the quantity of particles present. Cleanrooms are used in patient isolation and surgery where risks of infection exist. For more information, see Chapter 7, Health Care Facilities.

AIRBORNE PARTICLES AND PARTICLE CONTROL

Airborne particles occur in nature as pollen, bacteria, miscellaneous living and dead organisms, and windblown dust and sea spray. Industry generates particles from combustion, chemical vapors, and friction in manufacturing equipment. People in the workspace are a prime source of particles (e.g., skin flakes, hair, clothing lint, cosmetics, respiratory emissions, bacteria from perspiration). These airborne particles vary from 0.001 μm to several hundred micrometers. Particles larger than 5 μm tend to settle by gravity. In many manufacturing processes, these airborne particles are viewed as a source of contamination.

Particle Sources in Clean Spaces

In general, particle sources in clean spaces are grouped into two categories: external and internal.

External Sources. Externally sourced particles enter the clean space from the outside, normally via infiltration through doors, windows, and wall penetrations for pipes, ducts, etc. The largest external source is usually outside makeup air entering through the air conditioning.

In an operating cleanroom, external particle sources normally have little effect on overall cleanroom particle concentration because HEPA filters clean the supply air. However, the particle concentration in clean spaces at rest relates directly to ambient particle concentrations. External sources are controlled primarily by air filtration, room pressurization, and sealing space penetrations.

Internal Sources. People, cleanroom surface shedding, process equipment, and the manufacturing process itself generate particles in the clean space. Cleanroom personnel can be the largest source of internal particles, generating several thousand to several million particles per minute in a cleanroom. Personnel-generated particles are controlled with new cleanroom garments, proper gowning procedures, and airflow designed to continually shower workers with clean air. As personnel work in the cleanroom, their movements may re-entrain airborne particles from other sources. Other activities, such as writing, may also cause higher particle concentrations.

Particle concentrations in the cleanroom may be used to define cleanroom class, but actual particle deposition on the product is of greater concern. The sciences of aerosols, filter theory, and fluid motions are the primary sources of understanding contamination control. Cleanroom designers may not be able to control or prevent internal particle generation completely, but they may anticipate internal sources and design control mechanisms and airflow patterns to limit their effect on the product.

Fibrous Air Filters

Proper air filtration prevents most externally generated particles from entering the cleanroom. High-efficiency air filters come in two types: high-efficiency particulate air (HEPA) filters and ultralow-penetration air (ULPA) filters. HEPA and ULPA filters use glass fiber paper technology; laminates and nonglass media for special applications also have been developed. HEPA and ULPA filters are usually constructed in a minipleat form with either aluminum, coated string, filter paper, or hot-melt adhesives as pleating separators. Filters may vary from 1 to 12 in. in depth; available media area increases with deeper filters and closer pleat spacing.

Theories and models verified by empirical data indicate that interception and diffusion are the dominant capture mechanisms for HEPA filters. Fibrous filters have their lowest removal efficiency at the most penetrating particle size (MPPS), which is determined by filter fiber diameter, volume fraction or packing density, and air velocity. For most HEPA filters, the MPPS is 0.1 to 0.3 μm. Thus, HEPA and ULPA filters have rated efficiencies based on 0.3 and 0.12 μm particle sizes, respectively.

AIR PATTERN CONTROL

Air turbulence in the clean space is strongly influenced by air supply and return configurations, foot traffic, and process equipment layout. Selecting air pattern configurations is the first step of good cleanroom design. User requirements for cleanliness level, process equipment layout, available space for installing air pattern control equipment (i.e., air handlers, clean workstations, environmental control components, etc.), and project financial considerations all influence the final air pattern design selection.

Numerous air pattern configurations are used, but they fall into two general categories: unidirectional airflow (often mistakenly called laminar flow) and nonunidirectional airflow (commonly called turbulent).

Nonunidirectional Airflow

Nonunidirectional airflow has either multiple-pass circulating characteristics or nonparallel flow. Variations are based primarily on the location of supply air inlets and outlets and air filter locations. Examples of unidirectional and nonunidirectional airflow of pharmaceutical cleanroom systems are shown in Figures 2 and 3. Airflow is typically supplied to the space through supply diffusers with HEPA filters (Figure 2) or through supply diffusers with HEPA filters in the ductwork or air handler (Figure 3). In a mixed unidirectional and nonunidirectional system, outside air is prefiltered in the supply and then HEPA-filtered at workstations in the clean space (see the left side of Figure 3).

Nonunidirectional airflow may provide satisfactory contamination control for cleanliness levels of ISO 14644-1 Classes 6 through 8. Attaining desired cleanliness classes with designs similar to Figures 2 and 3 presupposes that the major space contamination is from makeup air and that contamination is removed in air-handler or ductwork filter housings or through HEPA filter supply devices.
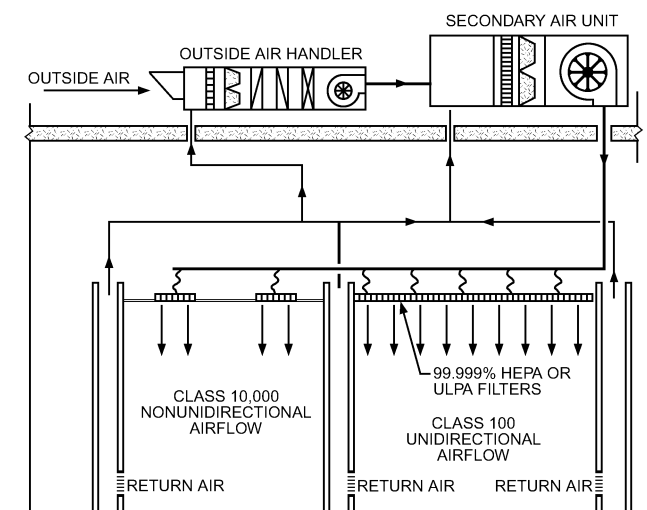
Fig. 2 Class 10,000 Nonunidirectional Cleanroom with Ducted HEPA Filter Supply Elements and Class 100 Unidirectional Cleanroom with Ducted HEPA or ULPA Filter Ceiling
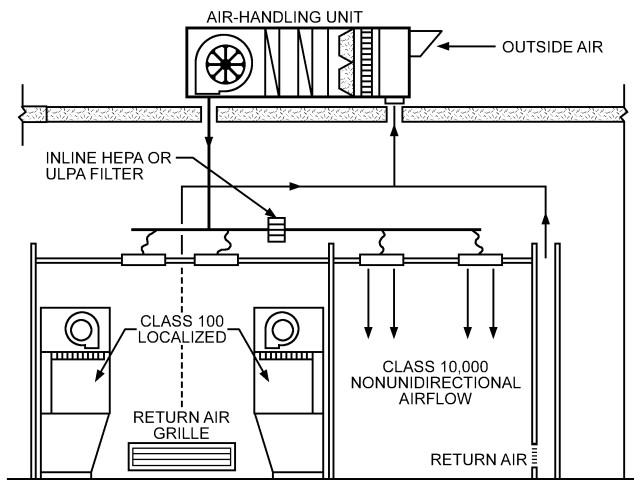
Fig. 3   Class 10,000 Nonunidirectional Cleanroom with HEPA Filters Located in Supply Duct and Class 100 Local Workstations

When internally generated particles are of primary concern, clean workstations are provided in the clean space.

Unidirectional Airflow

Unidirectional airflow, though not truly laminar, is characterized as air flowing in a single pass in a single direction through a cleanroom with generally parallel streamlines. Ideally, flow streamlines would be uninterrupted; although personnel and equipment in the airstream distort the streamlines, a state of constant velocity is approximated. Most particles that encounter an obstruction in unidirectional airflow continue around it as the airstream reestablishes itself downstream of the obstruction.

Air patterns are optimized and air turbulence is minimized in unidirectional airflow. In a **unidirectional-flow room**, air is typically introduced through ceiling HEPA or ULPA filters and returned through a raised access floor or at the base of sidewalls. Because air enters from the entire ceiling area, this configuration produces nominally parallel airflow. In a horizontal-flow cleanroom, air enters one wall and returns on the opposite wall.

A **downflow cleanroom** has a ceiling with HEPA filters. A cleaner-class cleanroom requires more HEPA filters; for an ISO Class 5 or cleaner room, the entire ceiling usually requires HEPA filtration. Ideally, a grated or perforated floor serves as the exhaust. This type of floor is inappropriate in pharmaceutical cleanrooms, which typically have solid floors and low-level wall returns.

In a downflow cleanroom, a uniform shower of air bathes the entire room in a downward flow of clean air. Contamination generated in the space does not move laterally against the downward flow of air (it is swept down and out through the floor) or contribute to build-up of contamination in the room.

Care must be taken in design, selection, and installation to seal a HEPA or ULPA filter ceiling. Properly sealed filters in the ceiling can provide the cleanest air presently available in a workroom.

In a **horizontal-flow cleanroom**, the supply wall consists entirely of HEPA or ULPA filters supplying air at approximately 90 fpm or less across the entire section of the room. Air then exits through the return wall at the opposite end of the room and recirculates. As with the downflow room, this design removes contamination generated in the space and minimizes cross contamination perpendicular to airflow. However, a major limitation to this design is that downstream air becomes contaminated. Air leaving the filter wall is the cleanest; it then becomes contaminated by the process as it flows past the first workstation. Process activities can be arranged to have the most critical operations at the clean end of the room, with progressively less

critical operations located toward the return air, or dirty end of the room.

ISO 14644-1 does not specify velocity requirements, so the actual velocity is as specified by the owner or owner's agent. The Institute of Environmental Sciences and Technology (IEST) published recommended air change rates for various cleanliness classes, which should be reviewed by the owner; however, the basis for the ranges is not known. Acceptable cleanliness has been demonstrated at lower air change rates, suggesting that results are depend more on filter efficiency and coverage than on air changes. Careful testing should be performed to ensure that required cleanliness levels are maintained. Other reduced-air-volume designs may use a mixture of high- and low-pressure-drop HEPA filters, reduced coverage in high-traffic areas, or lower velocities in personnel corridor areas.

Unidirectional airflow systems have a predictable airflow path that airborne particles tend to follow. Without good filtration practices, unidirectional airflow only indicates a predictable path for particles. However, superior cleanroom performance may be obtained with a good understanding of unidirectional airflow, which remains parallel to below the normal work surface height of 30 to 36 in., but deteriorates when it encounters obstacles (e.g., process equipment, work benches) or over excessive distances. Personnel movement also degrades flow, resulting in a cleanroom with areas of good unidirectional airflow and areas of turbulent airflow.

Turbulent zones have countercurrents of air with high velocities, reverse flow, or no flow at all (stagnancy). Countercurrents can produce stagnant zones where small particles may cluster and settle onto surfaces or product; they may also lift particles from contaminated surfaces and deposit them on product surfaces.

Cleanroom mockups may help designers avoid turbulent airflow zones and countercurrents. Smoke, neutral-buoyancy helium-filled soap bubbles, and nitrogen vapor fogs can make air streamlines visible in the mockup.

Computer-Aided Flow Modeling

Computer models of particle trajectories, transport mechanisms, and contamination propagation are commercially available. Flow analysis with computer models may compare flow fields associated with different process equipment, work benches, robots, and building structural design. Flow patterns and air streamlines are analyzed by computational fluid dynamics for laminar and turbulent flow where incompressibility and uniform thermophysical properties are assumed. Design parameters may be modified to determine the effect of airflow on particle transport and flow streamlines, thus avoiding the cost of mockups.

Major features and benefits associated with most computer flow models are

- Two- or three-dimensional modeling of simple cleanroom configurations, including people and equipment
- Modeling of unidirectional airflows
- Multiple air inlets and outlets of varying sizes and velocities
- Allowances for varying boundary conditions associated with walls, floors, and ceilings
- Aerodynamic effects of process equipment, workbenches, and people
- Prediction of specific airflow patterns, velocities, and temperature gradients of all or part of a cleanroom
- Simulation of room pressures by arranging supply, return, and exhaust airflows
- Reduced cost associated with new cleanroom design verification
- Graphical representation of flow streamlines and velocity vectors to assist in flow analysis (Figures 4 and 5)
- Graphical representation of simulated particle trajectories and propagation (Figure 6)
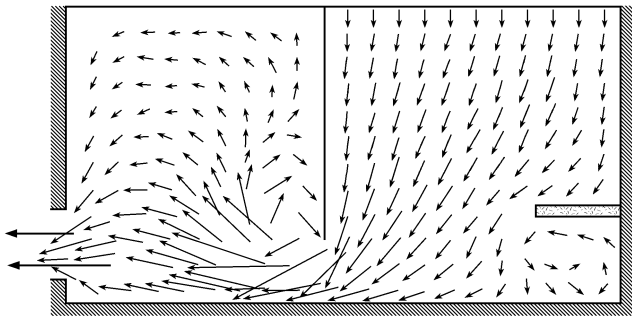
**Fig. 4   Cleanroom Airflow Velocity Vectors
Generated by Computer Simulation**
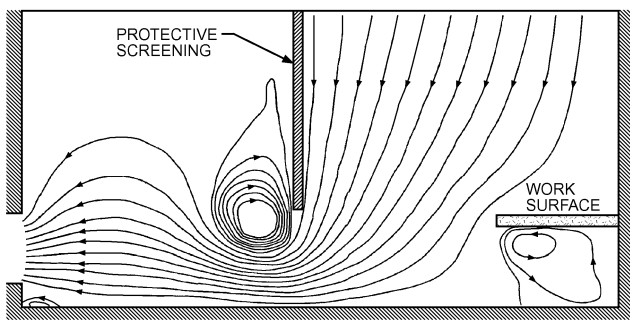
**Fig. 5   Computer Modeling of Cleanroom
Airflow Streamlines**
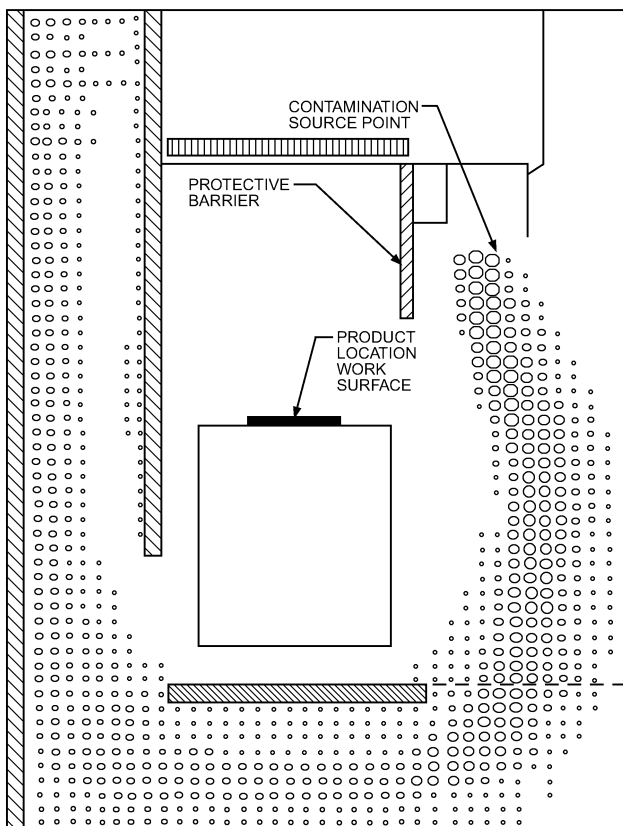
**Fig. 6   Computer Simulation of Particle
Propagation in Cleanroom**

Research has shown good correlation between flow modeling by computer and that done in simple mockups. However, computer flow modeling software should not be considered a panacea for cleanroom design because of the variability of individual project conditions.

AIRFLOW DIRECTION CONTROL AMONG ROOMS

Airflow direction control among cleanrooms with various levels of cleanliness is complex but critical to prevent airborne cross contamination. Nearby particulate contaminants could infiltrate a cleanroom through doors, cracks, passthroughs, and other penetrations for pipes, ducts, conduits, etc. An effective method of contamination control is pressurization: air moves from high pressure to low. Normally, the cleanest cleanroom should be designed with the highest pressure, with decreasing pressures corresponding to decreasing cleanliness. The desired flow path should be from the area of cleanest, to less clean, to less contaminated, and then to dirty areas.

Room Pressurization

Controlling contaminants in cleanrooms requires controlling the direction of airflow between adjacent spaces with various levels of cleanliness. This is equivalent to controlling the relative pressures between the spaces. Pressurization normally either directs desired flow patterns or isolates air cross contamination. Air pressure differences are created mechanically between rooms to introduce intentional air movement paths through room leakage openings. These openings could be designated (e.g., doorways) or undesignated (e.g., air gaps around doorframes, other cracks). Pressurization resists infiltration of unfiltered external sources of contaminants. It can be achieved by arranging controlled flow rates of supply, return, and exhaust airstreams to each room based on the following rules:

- *Pressurization*: entering (supply) airflow rate is higher than leaving (exhaust and/or return) airflow rate in the room; room offset flow is positive.
- *Depressurization*: entering (supply) airflow rate is lower than leaving (exhaust and/or return) airflow rate in the room; room offset flow is negative.

Differential pressure between any two rooms is normally designed at 0.05 in. of water or less. A room's differential airflow rate is often called **offset flow**, which is the sum of all leakage flows (in or out) in the room. Figure 7 shows the relationship between leakage flow rates at a specific pressure differential across an opening. Each curve on the chart represents a different leakage area. Once a leakage area along a doorframe is estimated, then leakage through the crack while the door is closed can be calculated based on the pressure difference across the door.

Room airtightness is the key element in the relationship between the room's flow offset value and the resulting pressure differential, and each room airtightness is unique and unknown unless tested. Treatment of a room's offset value defines a pressurization control strategy. Typical pressurization control techniques include the following:

- **Direct pressure-differential control (DP)** uses a pressure differential sensor to measure the pressure difference between a controlled room and an adjacent space (e.g., a corridor). DP is suitable for a tightly constructed room with limited traffic. It basically ignores the specific offset value as required; instead, it directly controls the airflow control devices to achieve the required pressure differential between the controlled room and an adjacent space. A door switch is recommended to trigger a reduced pressure-differential set point if the door opens.

LIVE GRAPH
Click here to view
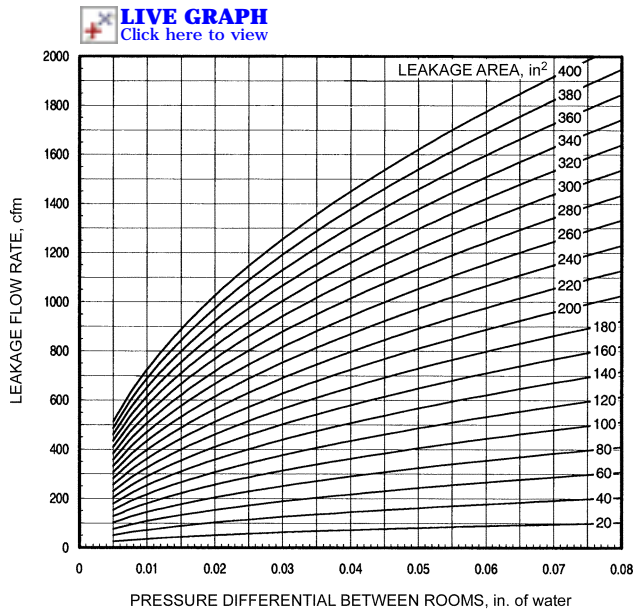
Fig. 7   Flow Rate through Leakage Area under Pressure Differential

- **Differential flow tracking control (DF)** assumes an offset value based on intuitive guesswork; this value is then used as a volumetric or mass flow difference between entering and leaving airflows through their airflow control devices. This method is suitable for open-style rooms or rooms with frequent traffic. DF normally maintains the same offset value throughout operation to keep pressurization constant. A constant-percentage offset value is sometimes used, but this creates a weaker pressurization at a lower flow.
- **Hybrid control (DF+DP)** (or **cascaded control**) combines the pressure accuracy of DP and the stability of DF. The offset value is resettable based on the pressure differential reading. The offset value reset schedule is predetermined, and the controller's parameters are fixed manually in field.

Multiple-Room (Suite) Pressurization

Pressurization for a suite of clean manufacturing spaces is more complex. In practice, air leakage interactions between the spaces have sometimes been neglected. However, because air leaking out of one space leaks into another, adjusting one room's offset value often affects adjacent rooms' previously balanced air pressures. Overlooking this fact can cause difficulties in commissioning and operation. Poorly designed pressurization could become unpredictable, unstable, or even fail to perform. For more information and procedures, consult the sources in the Bibliography.

A **room pressure and flow (P&F) diagram** for the controlled area (suite, zone, or floor) is often provided in design documents, and can be used as the basis of continuous validation and qualification of cleanroom pressure control. The P&F diagram should indicate

- Airflow design settings (values) of all supply, return, and exhaust registers for each room inside the controlled area
- Desired room pressure value with an acceptable tolerance in each pressure-controlled room
- Resulting leakage flow directions (due to room pressure differentials) and their estimated leakage flow values through doors at closed-door conditions

The three traditional control methods (DP, DF, and DF+DP) either ignore, assume, or manually fix in field the offset value, respectively. A better strategy is to control all rooms' pressures together as an optimized system, instead of independently. **Adap-**

tive DF+DP directly accounts for leakage flows between spaces in a suite, and actively adjusts each room's flow offset according to an online pressurization model. It uses flow and pressure differential measurements to estimate characteristics of leakage between spaces and adjust flow offsets automatically. This adaptive approach may be more suitable for suite pressurization. For design procedures and control strategies, see the related literature in the Bibliography.

TESTING CLEAN AIR AND CLEAN SPACES

Because early cleanrooms were largely for governmental use, testing procedures were set by government standards. U.S. *Federal Standard* 209 was widely accepted, because it defined air cleanliness levels for clean spaces around the world, but it was formally withdrawn in 2001. ISO standards now govern. Standardized testing methods and practices have been published by the Institute of Environmental Sciences and Technology (IEST), American Society for Testing and Materials (ASTM), and others.

Three basic test modes are used to evaluate a facility: (1) as built, (2) at rest, and (3) operational. A cleanroom cannot be fully evaluated until it has performed under full occupancy, and the process to be performed in it is operational. Thus, techniques for conducting initial performance tests and operational monitoring must be similar.

Sources of contamination are both external and internal for both unidirectional and nonunidirectional flow cleanrooms. The primary air loop is the major source of external contamination. Discrete particle counters using laser or light-scattering principles may detect particles of 0.01 to 5 µm. For particles 5 µm and larger, microscopic counting can be used, with particles collected on a membrane filter through which a sample of air has been drawn.

HEPA filters in unidirectional flow and ISO 14644-1 Class 5 ceilings should be tested for pinhole leaks at the filter media, sealant between media and filter frame, filter frame gasket, and filter bank supporting frames. The area between the wall or ceiling and the frame should also be tested. A pinhole leak at the filter bank can be extremely critical, because the leakage rate varies inversely as the square of the pressure drop across the hole. (The industry term *pinhole* used to describe the leak site is a misnomer. The size is almost never that of a hole formed by a pin, but is actually many times smaller.)

IEST testing procedures describe 12 tests for cleanrooms. Which tests are applicable to each specific cleanroom project must be determined.

PHARMACEUTICAL AND BIOMANUFACTURING CLEAN SPACES

Pharmaceutical product manufacturing facilities require careful assessment of many factors, including HVAC, controls, room finishes, process equipment, room operations, and utilities. Flow of equipment, personnel, and product must also be considered. It is important to involve designers, operators, commissioning staff, quality control, maintenance, constructors, and the production representative during the conceptual stage of design. Critical variables for room environment and types of controls vary greatly with the clean space's intended purpose. It is particularly important to determine critical parameters with quality assurance to set limits for temperature, humidity, room pressure, and other control requirements.

In the United States, regulatory requirements and specification documents such as 21CFR210 and 211, ISPE Design Guides, and National Fire Protection Association (NFPA) standards describe GMP. The goal of GMP is to achieve a proper and repeatable method of producing therapeutic, medical, and similar products free from microbial and particle contaminants.

In the United States, the one factor that differentiates pharmaceutical processing suites from other clean spaces (e.g., for electronic

and aerospace) is the requirement to pass U.S. Food and Drug Administration (FDA) inspection for product licensing. It is important to include the FDA's regulatory arms, the Center for Biologics Evaluation and Research (CBER) or the Center for Drug Evaluation and Research (CDER), early in the concept design process.

In addition, early in design, a qualification plan (QP) must be considered. Functional requirement specifications (FRS), critical parameters and acceptance criteria, installation qualification (IQ), operational qualification (OQ), and performance qualification (PQ) in the cleanroom suites are all required for process validation. IQ, OQ, and PQ protocols, in part, set the acceptance criteria and control limits for critical parameters such as temperature, humidity, room pressurization, air change rates, and operating particle counts (or air classifications). These protocols must receive defined approvals in compliance with the owner's guidelines. The qualification plan must also address SOPs, preventive maintenance (PM), and operator and maintenance personnel training.

Biomanufacturing and pharmaceutical aseptic clean spaces are typically arranged in suites, with clearly defined operations in each suite. For example, common convention positions an aseptic core (ISO 14644-1 Class 5) filling area in the innermost room, which is at the highest pressure, surrounded by areas of descending pressure and increasing particulate classes and bacterial levels (see Figure 8).

In aseptic processing facilities, the highest-cleanliness area is intentionally placed within lower-cleanliness areas and separated by room air classification and air pressure differences by air locks. A common pressure difference is about 0.05 in. of water or less between air classifications, with the higher-cleanliness room having the higher pressure. Lower pressure differences may be acceptable if they are proven effective. A pressure differential is generally

accepted as good manufacturing practice to inhibit particles from entering a clean suite.

Multiple levels (steps) of pressurizations are required to create cascaded airflows, which should flow from the cleanest rooms to the least clean. Normally, three pressure steps are commonly used for biosafety level (BSL) 3 and ISO Class 6, 7, or 8 applications; four pressure steps are desirable for BSL-4, Class 5 or cleaner applications. Air locks are effective at minimizing potential particle contamination from surrounding nonclassified or less-clean areas; selection depends on the type of cleanroom (Figure 9), because some that involve fume or biological agent operations may have a containment provision. For biological agent operations, the U.S. Centers for Disease Control and Prevention (CDC) and National Institutes of Health (NIH) define four biosafety levels (BSL-1 to BSL-4).

An air lock is an intermediate room between adjacent areas to prevent airborne cross contamination. Based on relative room pressure levels, air locks can be classified as follows:

- **Cascading:** Air lock pressure is between pressures in cleanroom and corridor
- **Bubble:** Air lock pressure is above pressures in cleanroom and corridor
- **Sink:** Air lock pressure is below pressures in cleanroom and corridor
- **Dual-compartment:** A bubble and a sink air lock are connected

Double-door air locks are often used at cleanroom entrances and exits. It is assumed that, if both doors are not open at the same time, cross contamination can be avoided. However a **required time delay (RTD)** needs to be specified between door openings, to minimize possible contamination during door opening. The RTD should be long enough for HEPA-filtered clean supply air to partially or fully replace the entire air volume of the air lock room at least once before the second door is allowed to open.

Design Concerns for Pharmaceutical Cleanrooms

The owner and designer must define the tolerable range of variable value (**acceptance criterion**) for each critical parameter. In that range, the product's safety, identity, strength, purity, and quality are not affected. The owner should define **action alarm** points at the limits of acceptance criteria, beyond which exposed product may be adulterated. The designer should select tighter (but achievable) target design values for critical parameters (in the range of acceptance criteria) and for noncritical parameters.

Facilities manufacturing penicillin or similar antibiotics (e.g., cephalosporins) must be physically isolated from other manufacturing areas and served by their own HVAC system. Some other products may require similar separation.

Facilities manufacturing aseptic/sterile products derived from chemical synthesis may have different requirements than those manufacturing biological or biotechnological products. The owner must define the inspecting agency's requirements.

The United States Pharmacopoeia (USP) limits temperatures to which finished pharmaceutical products may be exposed to 59 to 86°F. The production facility may need tighter limits than these, based on the owner's observed product data. Personnel comfort is a factor in design. Personnel perspiring in their protective overgarments can increase particulate and microbial counts, so lower temperatures and tighter temperature control may be advantageous.

Relative humidity may be critical to the product's integrity. Some products are processed or packaged cold and need a low room dew point to prevent condensation on equipment and vials. Some products are hygroscopic and require lower humidity than a condensing coil can provide; desiccant dehumidification should be considered. Humidification is usually needed for personnel comfort but not usually for product needs; it may also be needed where dust might present an explosion hazard or where low humidity may

Fig. 8 Typical Aseptic Suite

AIRFLOW   CORRIDOR +

AIR LOCK ++

AIRFLOW

CLEANROOM +++

A. CASCADING

AIRFLOW   CORRIDOR +

AIR LOCK ++

AIRFLOW

CLEANROOM −

B. BUBBLE

AIRFLOW   CORRIDOR +

AIR LOCK − −

AIRFLOW

CLEANROOM −

C. SINK

AIRFLOW   CORRIDOR −

AIR LOCK ++   AIR LOCK − −

CLEANROOM −   AIRFLOW

D. DUAL-COMPARTMENT

CLEANROOM AIR LOCK APPLICATION STRATEGIES

Type of Cleanroom	Air Lock Type	Purpose of Air Lock	Relative Pressure Relationship
• Positive pressure • No fume or bio agent • No containment needed	Cascading	• Prevent cleanroom being contaminated by dirty corridor air • Prevent cleanroom being contaminated from surrounding spaces through cracks	Cleanroom: +++ Air lock: ++ Corridor: +
• Negative pressure • Has fume or bio agent contamination • Containment needed	Bubble	• Prevent cleanroom being contaminated by dirty corridor air • Prevent cleanroom fume or bio agent releasing to corridor	Cleanroom: − Air lock: ++ Corridor: +
• Negative pressure • Has fume or bio agent contamination • Containment needed	Sink	• Prevent cleanroom being contaminated by dirty corridor air • Allow cleanroom fume or bio agent releasing to air lock. No personal protective equipment is needed	Cleanroom: − Air lock: − − Corridor: +
• Negative pressure • Has toxic fume or hazardous bio agent contamination, or has potent compound substances • Containment needed • Personal protection needed	Dual-Compartment	• Prevent cleanroom being contaminated by dirty corridor air • Prevent cleanroom fume or bio agent releasing to corridor • Personal protective equipment (such as pressurized suit and respirator) is required	Cleanroom: − Neg. Air lock: − − Pos. Air lock: ++ Corridor: −

Notes:
1. Excessive negative pressure in cleanroom is not recommended. If it is not surrounded by other clean spaces, untreated dirty air can infiltrate through cracks into cleanroom
2. A cleanroom service corridor often must be designed slightly positive or neutral pressure. Do not design for negative pressure unless a dual-compartment lock is used.

Fig. 9   Air Lock Types and Applications

hinder handling of dry materials. Clean steam (free of chemicals and other additives) is preferred for humidification because it is free of bacteria, but the humidification system should be free of amines or other contaminants if room air might contact the product.

Although airborne particles and viable organisms may be minimized by dilution (high air changes) and by supplying filtered air, the most effective control is to minimize release of these contaminants in the room. Personnel and machinery are the most common sources of contamination, and can be isolated from the product by gowning, masks, and isolation barriers. Careful study of how each room operates should reveal the most probable sources of contaminants and help the HVAC designer determine dilution air quantities and locate air supply outlets and returns. Avoid duct liners and silencers in supply air ductwork where contaminants can collect and bacterial and mold spores can accumulate. Ensure special attention is paid to cleaning and degreasing of metal sheeting and air ductwork before installation.

Airborne particle and microbe levels in aseptic processing areas are limited by government regulations, with lower limits for more critical rooms. European and FDA particle limits are for the room in operation, and can also be used conservatively as limits for the room at rest.

Facilities complying with U.S. cGMPs for aseptic processing must meet particle levels with manufacturing under way. (An exception is aseptic powder processing, in which airborne particulate levels at powder filling heads will exceed limits.) There should be no microbial contaminants in the critical-zone airstream, where filling and other critical activities occur; this area should be Class 100. The area immediately around the critical zone should be Class 10,000. If the critical area is within an isolator, then the area outside the isolator may be Class 100,000. Less critical support areas can be Class 100,000. For more detail on facility design, see FDA (2004).

According to the FDA (2004), 20 ach is usually sufficient for Class 100,000 rooms; Class 10,000 and 100 areas require significantly higher air change rates. Facility requirements for terminally sterilized products are not defined. E.U. (2003) also contains requirements for aseptic processing, and also addresses terminally sterilized products. Note that many facilities are constructed to meet both E.U. and U.S. cGMPs.

Restricted access barrier systems (RABS) are an alternative to a conventional cleanroom or isolator. Use of RABS should be approved by the manufacturer's quality unit during design.

Once product is in containers, the need for particulate control and minimum air changes is reduced or eliminated, depending on the degree of protection provided by product packaging. The owner should determine the necessary critical environmental parameters and acceptance criteria for each room and processing step.

Return openings for room HVAC should be low on the walls, to promote downward airflow from supply to return, sweeping contaminants to the floor and away from the product. In larger rooms, internal return air columns may be necessary. Perforated floors are discouraged because of difficulty cleaning them.

Aseptic facilities usually require pinhole-scanned (integrity-tested) HEPA filters (not ULPA) on supply air. Many operations install HEPA filters in the supply air to nonaseptic production facilities to minimize cross contamination from other manufacturing areas served by the HVAC. To increase the life of terminal HEPA filters in aseptic facilities, and to minimize the need to rebalance the supply system because of differential loading of terminal HEPA filters, many designers install a high-capacity HEPA bank downstream of the supply air fan, with constant-volume control to compensate for primary filter pressure changes and any dehumidifier airflow. The final HEPA filter is usually in a sealed gel frame or of a one-piece lay-in design that can be caulked to the ceiling frame, maintaining the integrity of the room envelope.

Aseptic product must be protected by pressurizing the room in which it is exposed, to about 0.05 in. of water above the next lower cleanliness room classification. To keep the pressure differential from dropping to zero when a door is opened, air locks are often used between rooms of different air pressure, especially at the entrance to the aseptic production room itself. Room pressure is a function of airflow resistance through cracks, openings, and permeable surfaces in the room shell. Consider all potential openings, slots, and door leakage that can affect the amount of air needed to pressurize the space. Because offset room airflow and room pressure are closely related, outdoor or makeup air requirements are often dictated by room pressures rather than by the number of occupants. The HVAC system should be able to handle more makeup air than needed for commissioning, because door seals can deteriorate over time.

ISO Class 5 unidirectional hoods are basically banks of HEPA filters, integrity-tested to be pinhole-free. Because it is difficult to maintain unidirectional flow for long distances or over large areas, the hood should be located as closely as possible to product exposure

sites (work surface). Hood-face velocity is usually 90 fpm or less, but the user should specify velocity and uniformity requirements. A unidirectional hood usually has clear sidewalls (curtains) to promote downward airflow and prevent entrainment of room particles into the hood's zone of protection. Curtains should extend below the product exposure site and be designed to prevent accidental disruption of airflow patterns by personnel. Many production facilities prefer rigid curtains for easier cleaning and sanitization.

Hood fan heat may become a problem, forcing the designer to overcool the room from which the hood draws its air or to provide sensible cooling air directly into the hood's circulating system.

Barrier Technology

Cleanrooms designed to meet ISO Class 5 or better require considerable equipment, space, and maintenance. Operating this equipment is expensive. Furthermore, cleanrooms typically need gowned operators inside to manipulate product and adjust machinery. Because the operator generates much of the contamination, it is better to place the operator outside the controlled environment; the volume of the controlled space can then be reduced, leading to substantially reduced capital and operating cost. Barrier technology or isolators are thus becoming increasingly popular.

Each isolator is designed to fit a specific application and is customized for its tasks. Applications vary widely based on product, process equipment, and throughput volume. Sterile barriers are typically positive-pressure envelopes around the filling equipment with multiple glove ports for operator access, constructed of polished stainless steel with clear, rigid view ports.

"Mouse holes" allow passage of vials in and out of the unit. Special transfer ports are used for stoppers and tools. Important design concerns include accessibility, ergonomics, interference with mating equipment, decontamination or sterilization procedures, access to service equipment, filter change, filter certification, process validation, and environmental control.

Extra attention must be paid to product filling, vial, and stopper protection; access to the barrier for sterilized stoppers; interface to the vial sterilization (depyrogenation) device; sterilizing product path, including pumps and tubing; and airflow patterns inside the barrier, especially at critical points. If hydrogen peroxide is to be used as a surface sterilant, care must be taken to ensure good circulation and adequate concentration inside the barrier, as well as removal of residual vapor in the required time frame.

Other barrier applications offer operator protection from potent compounds while maintaining a sterile internal environment. These tend to be total containment isolators with totally contained product transfer ports. All internal surfaces are sealed from the external environment or operator exposure. Because of potential chamber leaks, its internal pressure may be kept negative compared to the ambient space via exhaust fans, posing an additional potential risk to the product that must be addressed by the owner.

Nonsterile powder control may incorporate more passive barrier designs such as a downflow sample weighing hood. This arrangement takes advantage of unidirectional airflow to wash particles down and away from the operator's breathing zone. Low wall air returns at the back of the cubicle capture the dust. An arrangement of roughing and final filters allows air to return to the air handlers and back to the work zone through the ceiling. Products involving noxious or solvent vapors require a once-through air design. Barrier technology allows installation in environments that might require no special control or particulate classification. Because isolators and containment chambers are still relatively new to the pharmaceutical industry, installations for sterile product must be in a controlled ambient room condition of ISO Class 8.

Maintainability

A facility that considers maintainability (e.g., accessibility, frequency of maintenance, spare parts) in its design will be much more reliable and should have fewer operational and regulatory concerns. Many pharmaceutical facilities have been designed so that routine maintenance can be performed from outside the facility, except for unidirectional and terminal HEPA filters, which must be tested twice a year. Quality of materials is important to reliability, especially where failure can compromise a critical parameter. Consider how much exposure and risk to product and personnel are required during maintenance (e.g., how to clean the inside of a glove box contaminated by a toxic product). Beyond cleanable room surfaces that must be sanitized, consider whether and how HVAC equipment may be sanitized using the owner's procedures. Determine whether ductwork must be internally cleaned, and how.

Controls, Monitors, and Alarms

Room pressure may be maintained by passive (statically balanced) HVAC if there are few airflow variables. For example, the HVAC system for a few pressurized rooms may be statically balanced if there is a method of maintaining supply airflow volume to compensate for filter loading to ensure minimum room air changes. More complex designs may require dynamic room pressure control. Pressure controls should not overreact to doors opening and closing, because it is virtually impossible to pressurize a room to 0.05 in. of water with a door standing open. A door switch is often used to send a signal to room pressure control to avoid overreaction.

If room humidity must be maintained to tolerances tighter than the broad range that normal comfort cooling can maintain, active relative humidity control should be considered. If a desiccant dehumidifier is needed, unit operation over its range of flow must not adversely affect the ability of the HVAC to deliver a constant air supply volume to the facility.

Monitor and alarm critical parameters to prove they are under control. Log alarm data and parameter values during excursions. Logging may range from a local recorder to direct digital control (DDC) data storage with controlled access. Software source code should be traceable, with changes to software under the owner's control after qualification is complete. Commercial HVAC software is usually acceptable, but should be verified with regulatory agencies before detailed design begins. Also, keep complete calibration records for sensors, alarms, and recorders of critical parameter data.

Noise Concerns

HVAC noise is a common problem because fans must overcome the pressure drop of additional air filtration. The amount of noise generated must be reduced instead of adding duct silencers, which may harbor bacteria and are difficult to clean. Separate supply and return fans running at lower tip speeds instead of a single-fan air handler can reduce noise. HVAC noise may not be an issue if production equipment is considerably noisier.

Nonaseptic Products

Nonaseptic pharmaceutical facilities (e.g., for topical and oral products) are similar in design to those for aseptic product manufacturing, but with fewer critical components to be qualified. However, critical parameters such as room humidity may be more important, and airborne particle counts are not considered in the United States. If the product is potent, barrier isolation may still be advisable. Room differential pressures or airflow directions and air changes are usually critical (needed to control cross contamination of products), but no regulatory minimum pressure or air change values apply.

START-UP AND QUALIFICATION OF PHARMACEUTICAL CLEANROOMS

Qualification of HVAC for Aseptic Pharmaceutical Manufacturing

Qualification of the pharmaceutical cleanroom HVAC is part of the overall commissioning of the building and its equipment, except

that documentation is more rigorous. Qualification covers equipment affecting critical parameters and their control. Other groups in the manufacturing company (e.g., safety or environmental groups) may require similar commissioning documentation for their areas of concern. The most important objectives in meeting the approving agency's requirements are to (1) state what procedures will be followed and verify that it was done, and (2) show that product is protected and room acceptance criteria are met.

Qualification Plan and Acceptance Criteria

Early in design, the owner and designer should discuss who will be responsible for as-built drawings, setting up maintenance files, and training. They should create a qualification plan for the HVAC, including (1) a functional description of what the systems do; (2) maps of room pressures, airflow diagrams, and cleanliness zones served by each air handler; (3) a list of critical components to be qualified, including the computer controlling the HVAC; (4) a list of owner's procedures that must be followed for qualification of equipment and systems that affect critical variables; (5) a list of qualification procedures (IQ/OQ/PQ protocols) written especially for the project; and (6) a list of needed commissioning equipment.

The approval procedure should also be defined in the QP. It is important to measure and document critical variables of a system (e.g., room pressure), but it is also important to document performance of components that affect that critical variables (e.g., room pressure sensors, temperature sensors, airflow volume monitor) for GMP as well as business records. Documentation helps ensure that replacement parts (e.g., motors) can be specified, purchased, and installed to satisfy critical variables.

It is important to determine what the critical components are (including instruments) that could affect critical parameters and could, through an undetected failure, lead to product adulteration. This may be accomplished by a joint effort between the HVAC engineer, owner, and a qualified protocol writer. If performance data are in the qualification records, replacement parts of different manufacture can be installed without major change control approvals, as long as they meet performance requirements. Owner approvals for the qualification plan should be obtained during detailed design.

Qualification requires successfully completing the following activities for critical components and systems. The designer should understand the requirements for owner's approval of each protocol (usually, the owner approves the blank protocol form and the subsequently executed protocol).

The **installation qualification (IQ)** protocol records construction inspection to verify compliance with contract documents, including completion of punch list work, for critical components. It may include material test reports, receipt verification forms, shop inspection reports, motor rotation tests, and contractor-furnished testing and balancing. It also includes calibration records for instrumentation used in commissioning and for installed instrumentation (e.g., sensors, recorders, transmitters, controllers, and actuators) traceable to National Institute of Standards and Technology (NIST) instruments.

Control software should be bench tested, and preliminary (starting) tuning parameters should be entered. Control loops should be dry-loop checked to verify that installation is correct. Equipment and instruments should be tagged and wiring labeled. Commissioning documentation must attest to completion of these activities and include as-built drawings and installation/operation/maintenance (IOM) manuals from contractors and vendors.

The **operational qualification (OQ)** protocol documents startup, including critical components. This includes individual performance testing of control loops under full operating pressure performed in a logical order (i.e., fan control before room pressure control). The commissioning agent must verify that operating parameters are within acceptance criteria.

The HVAC may be challenged under extremes of design load (where possible) to verify operation of alarms and recorders, to determine (and correct, if significant) weak points, and to verify control and door interlocks. Based on observations, informal alert values of critical parameters, which might signify abnormal operation, may be considered. Although product would not be adulterated at these parameter values, staff could assess an alarm and react to it before further deviations from normal operation occurred.

Documented smoke tests verify space pressure and airflow in critical rooms or inside containment hoods, and show airflow patterns and directions around critical parts of production equipment. Many smoke tests have been videotaped, especially when room pressure differentials are lower than acceptance criteria require and cannot be corrected.

Files should include an updated description of the HVAC, describing how it operates, schematics, airflow diagrams, and room pressure maps that accompany it. Copies should be readily accessible and properly filed. Operating personnel should be familiar with the data in these records and be able to explain it to an agency inspector.

Other Documents. GMP documents should also include test reports for HEPA filters (efficiency or pinhole-scan integrity tests) at final operating velocities. If the filter installer performed the tests, the data should be part of the IQ package.

Documents should verify that instruments display, track, and store critical parameters and action alarms. (Consider recording data by exception and routine documentation of data at minimal regular frequency.)

Systems and equipment should be entered into the owner's maintenance program, with rough drafts of new maintenance procedures (final drafts should reflect commissioning experience).

Records should attest to the completion of these activities, including final as-built and air and water balance reports.

Performance qualification (PQ) is proof that the entire HVAC performs as intended under actual production conditions. PQ is the beginning of ongoing verification that the system meets acceptance criteria of the product (often called validation). This includes documentation of

- Maintenance record keeping and final operating and maintenance procedures in place, with recommended frequency of maintenance, and (at the owner's option) a procedure for periodic challenge of controls and alarms
- Logs of critical parameters that prove the system maintains acceptance criteria over a prescribed time
- Training records of operators and maintenance personnel
- Final loop tuning parameters

After accepting PQ, the owner's change control procedure should limit further modifications to critical components (as shown on IQ and OQ forms) that affect the product. Much of the building's HVAC equipment should not need qualification, but records for the entire facility should be kept and problems corrected before they become significant. Records of corrections should also be kept.

Once the system is operational, pharmaceutical product trial lots are run in the facility (process validation) and the owner should regularly monitor viable (microbial) and nonviable particles in the room.

SEMICONDUCTOR CLEANROOMS

Cleanroom Advances with Modern Process Technology

Since the mid-1990s, most microelectronic facilities manufacturing semiconductors have required cleanrooms providing ISO Class 3 and cleaner for wafer fabs and Class 5 to 8 for auxiliary manufacturing rooms. This state-of-the-art cleanroom technology has been driven by the decreasing size of microelectronic circuitry and larger wafer sizes. A deposited particle with a diameter of 10% of the circuit width may cause a circuit to fail. Many facilities are designed to meet as-built air cleanliness of less than one particle 0.1 μm and larger per cubic foot of air.

Currently, semiconductor manufacturing cleanroom integration is important in semiconductor facilities design. Larger wafers require larger processing equipment. Cleanroom structures are now integrated into the process and mechanical systems to reduce overall building height and construction cost, and to shorten construction duration. In addition, particle control has advanced to the level of molecular contamination control. Product contamination control also includes internal contaminations such as chemical, ionic, and static electricity control, and fire resistance performance.

Semiconductor Cleanroom Configuration

Semiconductor cleanrooms today are of two major configurations: clean tunnel or open-bay (ballroom). The **clean tunnel** is composed of narrow modular cleanrooms that may be completely isolated from each other. Fully HEPA- or ULPA-filtered pressurized plenums, ducted HEPA or ULPA filters, or individual fan modules are used. Production equipment may be located in the tunnel or installed through the wall where a lower-cleanliness (nominally ISO Class 7 or cleaner) service chase is adjacent to the clean tunnel. The service chase is used in conjunction with sidewall return or a raised floor, possibly with a basement return.

The primary advantage of the tunnel is reduced HEPA- or ULPA-filter coverage and ease of expanding additional tunnel modules into unfiltered areas. The tunnel is typically 8 to 14 ft wide. If the tunnel is narrower, production equipment cannot be placed on both sides; if wider, flow becomes too turbulent and tends to break toward the walls before it leaves the work plane. Figure 10 shows a clean tunnel.

The tunnel design has the drawback of restricting new equipment layouts. Cleanroom flexibility is valuable to semiconductor manufacturing. As processes change and new equipment is installed, the clean tunnel may restrict equipment location to the point that a new module must be added. The tunnel approach may complicate moving product from one type of equipment to another.

Fan/filter clean tunnels have a wide range of applications. However, the noise generated by fans is directly distributed to the tunnel, and the unit's efficiency is lower than in central station recirculating systems. Life-cycle cost analysis can be used (among other considerations) to determine the appropriate configuration.

Ballroom or **open-bay design** involves large (up to 100,000 ft^2) open-construction cleanrooms. Interior walls may be placed wherever manufacturing logistics dictate, providing maximum equipment layout flexibility. Replacing process equipment with newer equipment is an ongoing process for most wafer fabrication facilities; support services must be designed to handle different process equipment layouts and even changes in process function. Often, a manufacturer may completely redo equipment layout if a new product is being made.

Open-bay designs can use either a pressurized plenum or ducted filter modules, although pressurized plenums are becoming more common. Pressurized plenums usually are recirculating air plenums, in which makeup air mixes with recirculating air or is ducted to the recirculating units (Figure 11). Either one large plenum with multiple supply fans or small adjacent plenums are acceptable. Small plenums allow shutting down areas of the cleanroom without disturbing other clean areas, and may also include one or more supply fans.

In the past decade, silicon wafer diameter has increased threefold. Along with the requirement for larger process equipment, the demand for larger room sizes has also become increasingly significant. Major semiconductor facilities, with total manufacturing areas of 30,000 ft^2 and larger, may use both open-bay and tunnel design configurations. Flexibility to allow equipment layout revisions warrants the open-bay design. Process equipment suitable for through-the-wall installation, such as diffusion furnaces, may use either design. Equipment such as lithographic steppers and coaters must be located entirely in laminar flow; thus, open-bay designs are more suitable. Which method to use should be discussed among the cleanroom designer, production personnel, and contamination control specialist.

Building structure areas are sometimes used as recirculating and makeup air units, fan deck, and plenum. Some structures perform as very large cabinets of makeup air units or recirculating units. Figure 12 shows a building truss level arranged as a fan deck and air plenum. Coordination between architects, engineers (structural, process, and mechanical), semiconductor facilities personnel, and construction industries must continue to minimize building size and to satisfy ever-evolving process requirements.

Many semiconductor facilities contain separate cleanrooms for process equipment ingress into the main factory. These ingress areas are staged levels of cleanliness. For instance, the equipment receiving and vacating area may be ISO Class 8 (Class 100,000), and the preliminary equipment setup and inspection area may be ISO Class 7 (Class 10,000). The final stage, where equipment is cleaned and final installation preparations are made before the fabrication entrance, is ISO Class 6 (Class 1000). Some staged cleanrooms must have adequate clear heights to allow forklift access for equipment subassemblies.

Airflow in Semiconductor Cleanrooms

Current semiconductor industry cleanrooms use vertical unidirectional airflow, which produces a uniform shower of clean air throughout the entire cleanroom. Particles are swept from personnel and process equipment, with contaminated air leaving at floor level; this produces clean air for all space above the work surface.

In vertical unidirectional airflow, the cleanroom ceiling area consists of HEPA or ULPA filters set in a nominal grid size of 2 by 4 ft, T-bar-style grid with gasketed or caulked seals for many ISO Class 5 systems; Class 3 and Class 4 systems often use either low-vapor-pressure petrolatum fluid or silicone dielectric gel to seal the filters into a channel-shaped ceiling grid. Whether T-bar or channel-shaped grids are used, the HEPA or ULPA filters normally cover 85 to 95% of the ceiling area, with the rest of the ceiling area composed of grid work, lighting, and fire protection sprinkler panels.

HEPA or ULPA filters in vertical unidirectional airflow designs are installed (1) with a pressurized plenum above the filters, (2) through individually ducted filters, or (3) with individually fan-powered filter modules. A system with a plenum must provide even pressurization to maintain uniform airflow through each filter. Ducted HVAC typically has higher static pressure loss from the ducting and balance dampers, resulting in higher fan energy and higher operating cost. Maintenance costs may also be higher
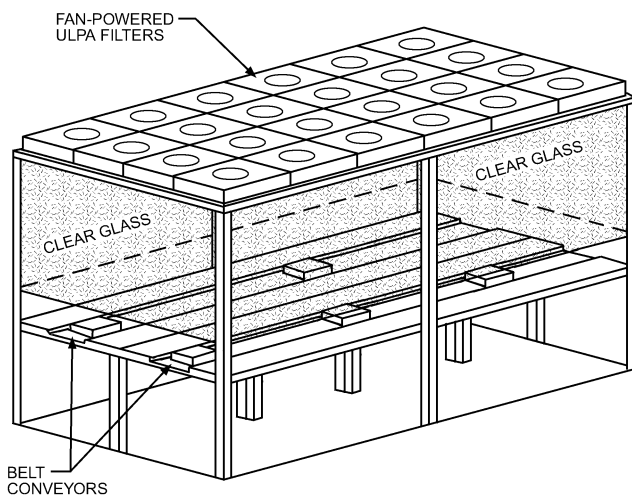
Fig. 10   Elements of a Clean Tunnel
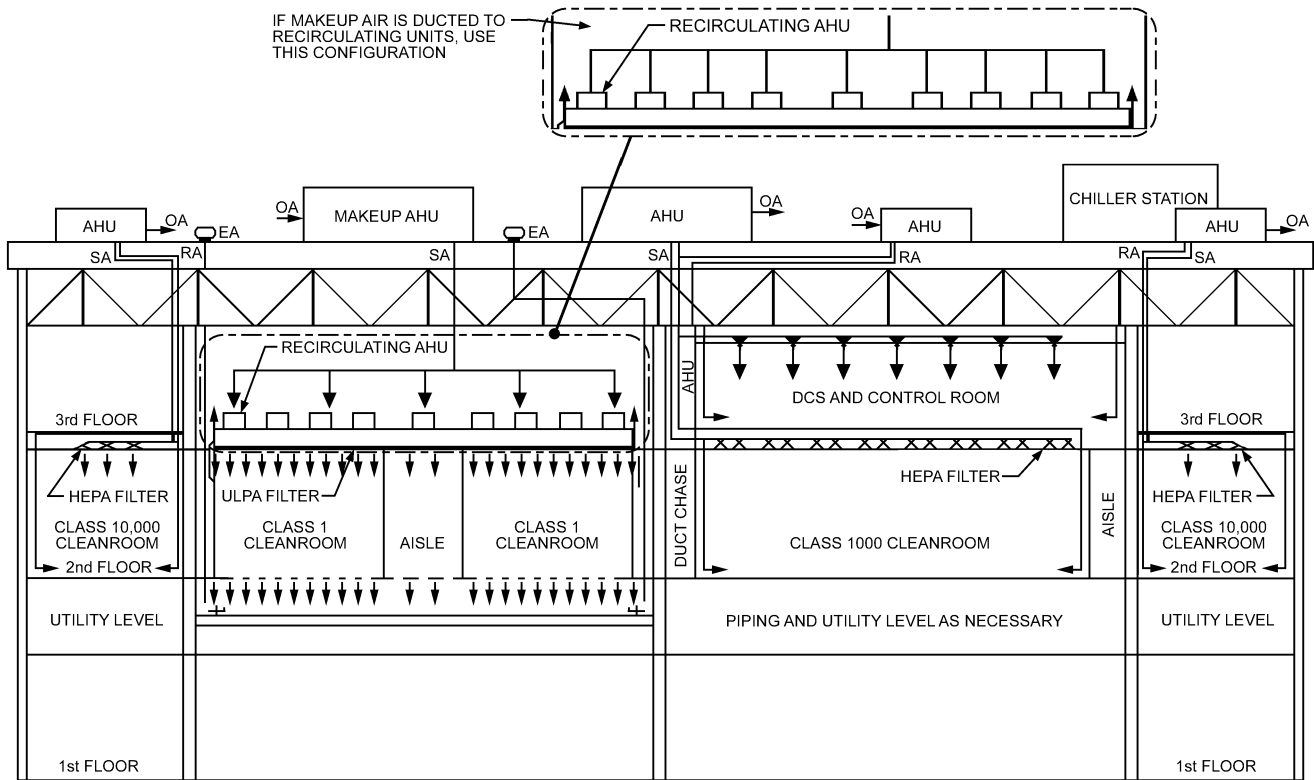
Fig. 11   Typical Semiconductor Manufacturing Plant Section View
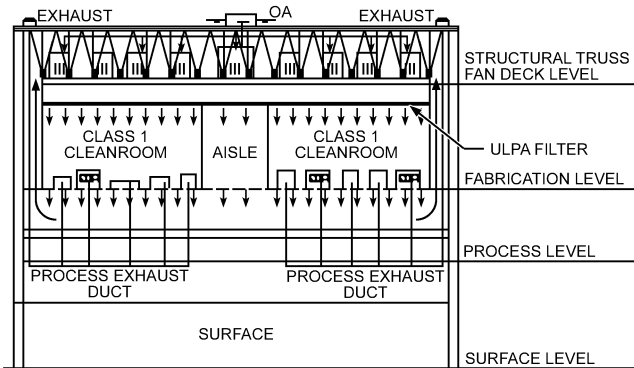
Fig. 12   Building Truss Level Arranged as Fan Deck and Air Plenum

incurred because of the balance method involved with ducted HVAC.

Individual fan-powered filter modules use fractional horsepower fans (usually forward-curved fans) that provide airflow through one filter assembly. This method allows airflow to be varied throughout the cleanroom and requires less space for mechanical components. Disadvantages are the large number of fans involved, low fan and motor efficiencies because of the small sizes, potentially higher fan noises, and higher operation and maintenance costs.

When through-the-floor return grating is used, a basement return is normally included to provide a more uniform return as well as floor space for dirty production support equipment.

Sidewall returns are an alternative to through-the-floor returns; however, airflow may not be uniform throughout the work area.

These returns are most applicable for ISO Class 5 to 8 (Class 100 to 100,000) cleanrooms.

Prefiltration is an economical way to increase ULPA filter life. Prefilters are located in recirculation airflow, in either the return basement or air handler, to allow replacement without disrupting production.

Cleanroom Air Velocity and Air Changes

For a given cleanroom, the supply air volume Q (cfm) is

$$Q = LWv \tag{1}$$

$$\text{ach} = \frac{60Q}{LWH} \tag{2}$$

or

$$\text{ach} = \frac{60LWv}{LWH}$$

$$\text{ach} = \frac{60v}{H} \tag{3}$$

where

    L = room length, ft
   W = room width, ft
   H = room height, ft
    v = room air velocity, fpm
ach = air changes per hour

From Equation (3), the number of air changes per hour is inversely proportional to the height of the room: the greater the height of the cleanroom, the fewer air changes per hour required, and vice versa.

Air Ionization. In addition to cleanroom particle control with fiber filters, air ionization can be used to control particle attraction

Table 3 Air Changes per Hour Versus Vertical Airflow Velocities, Room Heights, and Cleanliness Classes

ISO Class	FS209 Class	Velocity, fpm	Air Changes per Hour for ceiling Height, ft							
			40	50	60	80	100	120	140	160
2	–	85 to 100	128 to 150	102 to 120	85 to 100	—	—	—	—	—
3	1	70 to 85	105 to 128	84 to 102	70 to 85	52 to 64	—	—	—	—
4	10	60 to 70	90 to 105	72 to 84	60 to 70	45 to 52	36 to 42	—	—	—
5	100	45 to 55	68 to 83	54 to 66	45 to 55	34 to 41	27 to 33	22 to 27	—	—
6	1000	25 to 35	38 to 53	30 to 42	25 to 35	19 to 26	15 to 21	12 to 18	10 to 15	—
7	10,000	8 to 16	12 to 24	10 to 19	8 to 16	6 to 12	5 to 10	4 to 8	3 to 6	3 to 2
8	100,000	4 to 6	8 to 10	5 to 7	4 to 6	3 to 4	2 to 3	2 to 3	2	2
9	1,000,000	2 to 3	3 to 5	2 to 3	2 to 3	2	1 to 2	1 to 2	1	1

to product surfaces by eliminating electrostatic discharge and static charge build-up. However, the emitter tip material must be carefully selected to prevent depositing particles on the product.

HIGH-BAY CLEANROOMS

High-bay cleanrooms have ceiling heights between 40 and 160 ft, with the higher ceilings used primarily in the aerospace industry for producing and testing missiles, launch vehicles, rocket engines, and communication and observation satellites, and lower ceilings used in jet aircraft assembly, painting, and cleaning operations; and in crystal-pulling areas in semiconductor chips manufacturing facilities.

Most high-bay cleanrooms are designed to meet ISO Class 7, Class 8 or higher as required by some U.S. Air Force and U.S. Navy specifications. Crystal-pulling cleanrooms for semiconductor microchips are usually specified at Class 5 to Class 6 range.

Table 3 shows approximate ranges of ceiling-height-dependent airflow per minute and air changes per hour by cleanroom classes derived from Equation (3).

Downflow and Horizontal-Flow Designs

In **downflow designs**, air is delivered in a unidirectional (or simulated unidirectional) flow pattern from the ceiling and returned through floor return openings or low sidewall returns. The objective is to shower the object from above so that all particles are flushed to the returns. The supply air terminals may be HEPA-filter or high-volume air diffusers. Downflow rooms allow space flexibility because more than one device may be worked on in the room at the same air cleanliness level.

The disadvantage is the relative difficulty of balancing airflow. High-bay cleanrooms typically have concrete floors that may include trenches to return some of the air not taken in at low sidewall returns. Special care must be taken to ensure clean air at the object because the laminar flow of the air disintegrates. At the low velocities typical of unidirectional design, pathways may be created toward the returns, causing the clean air to miss the object. Any activity in the cleanroom that generates even a small amount of heat produces updrafts in downward-flowing supply air.

Horizontal-flow designs are always unidirectional, with the cleanest air always available to wash the object in the room. Properly designed horizontal rooms are easier to balance than vertical-flow rooms because supply and return air volumes may be controlled at different horizontal levels in the room.

The main disadvantage of horizontal-flow high-bay rooms is that they provide clean air for only one object, or at best, several objects in the same plane. Once past the object, air cleanliness degrades to the extent that the process generates particles.

Downflow designs are most widely used, but certain projects such as the space telescope and space shuttle assembly room may require horizontal-airflow high-bay cleanrooms (Figure 13).

Air Handling

Because of the large volume of air in a high-bay cleanroom, central recirculating fan systems are commonly used with minimum
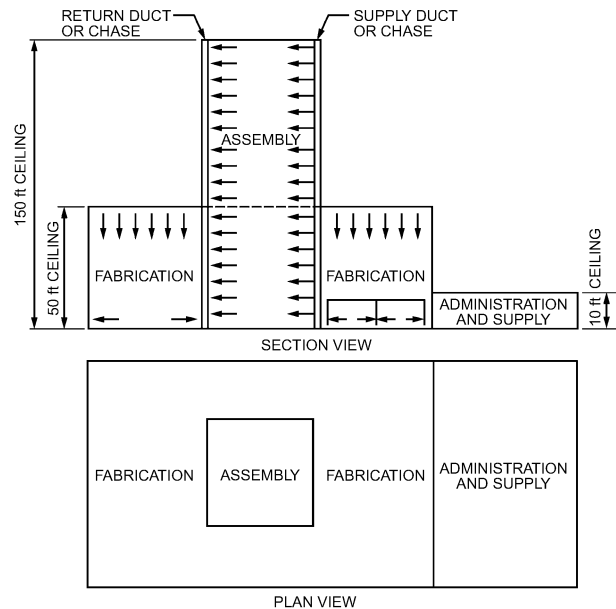
Fig. 13 High-Bay Cleanroom Scheme

heating and cooling capability. A separate injection air handler provides heating, cooling, and makeup air. The injection system must include volumetric controls to ensure proper building pressure.

Equipment and Filter Access

Air-handling equipment and prefilters should be accessible from outside the cleanroom. Adequate provision must be made for changing filters if air is distributed to the cleanroom with HEPA filters at the room entry. In horizontal-flow cleanrooms, access should be from the upstream (pressure) side, and service scaffolds should be incorporated at least every 8 ft in height of the filter bank. Downflow ceiling filters in T-bar or gel-seal ceilings must be accessed from below using an approved gantry crane with full mobility across the ceiling. Prefilters in the main air supply should be placed in built-up frames with both upstream and downstream access. A HEPA filter bank remote from the room air-distribution system should be installed in a built-up bank with a gel or clamp seal. Access doors must be installed up- and downstream for certification, scanning, and qualification testing.

Prefilter Selection

In any high-bay cleanroom class, air will pass through a final HEPA filter before entering the room; these final filters must be protected by prefilters. HEPA filters for recirculating air should be protected with 85% rated bag or rigid media filters with no other prefilters present than required. Makeup air should include minimum 85% ASHRAE filters on the fan inlet and minimum 95% dispersed oil particulate (DOP) filters on the fan discharge.

Design Criteria and Indoor Air Quality

The indoor design temperature range for aerospace and aircraft manufacturing cleanrooms is $73 \pm 5°F$, with the higher temperatures commonly used in summer, and the lower ones in winter. However, the user should provide guidance on specific required room temperature requirements. In semiconductor crystal-pulling cleanroom design, room temperature is usually required at a constant level of $72 \pm 0.5°F$.

Another key parameter is relative humidity. For aerospace and aircraft manufacturing cleanrooms, relative humidity should not exceed 60%; semiconductor crystal-pulling cleanrooms usually require indoor relative humidity to be $50 \pm 5\%$ as design base.

Other issues include noise and vibration from process and HVAC equipment, and dusts, fumes, smoke, odors, vapors, moistures and gaseous generated during welding, sanding, painting, washdown, fuel filling, etc. See Chapters 7, 8, 9, 12, and 13 of the 2005 *ASHRAE Handbook—Fundamentals* for additional information.

ENVIRONMENTAL SYSTEMS

Cooling Loads and Cooling Methods

Two major internal heat load components in cleanroom facilities are process equipment and fans. Because most cleanrooms are located entirely within conditioned space, traditional heat sources of infiltration, fenestration, and heat conductance from adjoining spaces are typically less than 2 to 3% of the total load. Some cleanrooms have been built with windows to the outside, usually for daylight awareness, and a corridor separating the cleanroom window from the exterior window.

The major cooling sources designed to remove cleanroom heat and maintain environmental conditions are makeup air units, primary and secondary air units, and the process equipment cooling system. Some process heat, typically from electronic sources in computers and controllers, may be removed by process exhaust.

Fan energy is a very large heat source in ISO Class 4 or better cleanrooms. Recirculated room airflow rates of 90 fpm or less (500+ ach) are typical for these facilities.

Latent loads are primarily associated with makeup air dehumidification. A low dry-bulb leaving air temperature, associated with dehumidified makeup air, supplements sensible cooling. Supplemental cooling by makeup air may account for as much as 300 Btu/h per square foot of cleanroom.

Process cooling water (PCW) is used in process equipment heat exchangers, performing either simple heat transfer to cool internal heat sources, or process-specific heat transfer, in which the PCW contributes to the process reaction.

The diversity of manufacturing heat sources (i.e., the portion of total heat transferred to each cooling medium) should be well understood. When bulkhead or through-the-wall equipment is used, equipment heat loss to support chases versus to the production area affects the cooling design when the support chase is served by a different cooling system than the production area.

Makeup Air

Control of makeup air and cleanroom exhaust affects cleanroom pressurization, humidity, and room cleanliness. Makeup airflow requirements are dictated by the amount required to replace process exhaust and by air volumes for pressurization. Makeup air volumes can be much greater than the total process exhaust volume to provide adequate pressurization and safe ventilation.

Makeup air is frequently introduced into the primary air path on the suction side of the primary fan(s) to enhance mixing. Makeup air volumes are adjusted with zone dampers and makeup fan controls using speed controllers, inlet vanes, etc. Opposed-blade dampers should have low leak characteristics and minimum hysteresis.

Makeup air should be filtered before injection into the cleanroom. If the makeup air is injected upstream of the cleanroom ceiling

ULPA or HEPA filters, minimum 95% efficient filters (ASHRAE *Standard* 52.1) should be used to avoid high dust loading and reduced HEPA filter life.

In addition, 30% efficient prefilters followed by 85% filters may be used to prolong the life of the 95% filter. When makeup air is injected downstream of the main HEPA filter, further HEPA filtering of the makeup air should be added to the prefilters. In addition to particle filtering, many makeup air handlers require filters to remove chemical contaminants (e.g., salts and pollutants from industries and automobiles) present in outside air. Chemical filtration may be accomplished with absorbers such as activated carbon or potassium permanganate impregnated with activated alumina or zeolite.

Process Exhaust

Process exhausts for semiconductor facilities handle acid, solvent, toxic, pyrophoric (self-igniting) fumes, and process heat exhaust. Process exhaust should be dedicated for each fume category, by process area, or by the chemical nature of the fume and its compatibility with exhaust duct material. Typically, process exhausts are segregated into corrosive fumes, which are ducted through plastic or fiberglass-reinforced plastic (FRP) ducts, and flammable (normally from solvents) gases and heat exhaust, which are ducted in metal ducts. Care must be taken to ensure that gases cannot combine into hazardous compounds that can ignite or explode in the ductwork. Segregated heat exhausts are sometimes installed to recover heat, or hot uncontaminated air that may be exhausted into the suction side of the primary air path.

Required process exhaust volumes vary from 1 cfm per square foot of cleanroom for photolithographic process areas, to 10 cfm per square foot for wet etch, diffusion, and implant process areas. When specific process layouts are not designated before exhaust design, an average of 5 cfm per square foot is normally acceptable for fan and abatement equipment sizing. Fume exhaust ductwork should be sized at low velocities (1000 fpm) to allow for future needs.

For many airborne substances, the American Conference of Governmental Industrial Hygienists (ACGIH) established requirements to avoid excessive worker exposure. The U.S. Occupational Safety and Health Administration (OSHA) set specific standards for allowable concentrations of airborne substances. These limits are based on working experience, laboratory research, and medical data, and are subject to constant revision. See *Industrial Ventilation: A Manual of Recommended Practices* (ACGIH 2004) to determine limits.

Fire Safety for Exhaust

ICC's (2003) *International Building Code* (IBC) designates semiconductor fabrication facilities as Group H occupancies. The Group H occupancy class should be reviewed even if the local jurisdiction does not use the IBC because it is currently the only major code in the United States specially written for the semiconductor industry and, hence, can be considered usual practice. This review is particularly helpful if the local jurisdiction has few semiconductor facilities.

Chapter 18 in ICC's (2003) *International Fire Code* (IFC) addresses specific requirements for process exhaust relating to fire safety and minimum exhaust standards. Chapter 27, Hazardous Materials, is relevant to many semiconductor cleanroom projects because of the large quantities of hazardous materials stored in these areas. Areas covered include ventilation and exhaust standards for production and storage areas, control requirements, use of gas detectors, redundancy and emergency power, and duct fire protection.

Temperature and Humidity

Precise temperature control is required in most semiconductor cleanrooms. Specific chemical processes may change under different temperatures, or masking alignment errors may occur because of product dimensional changes as a result of the coefficient of expansion. Temperature tolerances of $\pm 1°F$ are common, and precision of

±0.1 to 0.5°F is likely in wafer or mask-writing process areas. Wafer reticle writing by electron beam technology requires ±0.1°F, whereas photolithographic projection printers require ±0.5°F tolerance. Specific process temperature control zones must be small enough to control the large air volume inertia in vertical laminar flow cleanrooms. Internal environmental controls, which allow room tolerances of ±1°F and larger temperature control zones, are used in many process areas.

Within temperature zones of the typical semiconductor factory, latent heat loads are normally small enough to be offset by incoming makeup air. Sensible temperature is controlled with either (1) cooling coils in the primary air stream, or (2) unitary sensible cooling units that bypass primary air through the sensible air handler and blend conditioned air with unconditioned primary air.

In most cleanrooms of ISO Class 6 or better, production personnel wear full-coverage protective smocks that require cleanroom temperatures of 68°F or less. If full-coverage smocks are not used, higher temperature set points are recommended for comfort. Process temperature set points may be higher as long as product tolerances are maintained.

Semiconductor humidity levels vary from 30 to 50% rh. Humidity control and precision are functions of process requirements, prevention of condensation on cold surfaces in the cleanroom, and control of static electric forces. Humidity tolerances vary from 0.5 to 5% rh, primarily dictated by process requirements. Photolithographic areas have more precise standards and lower set points. The exposure timing of photoresists (used in photolithography) can be affected by varying relative humidity. Negative resists typically require low (35 to 45%) relative humidity. Positive resists tend to be more stable, so the relative humidity can go up to 50% where there is less of a static electricity problem.

Independent makeup units should control the dew point in places where direct-expansion refrigeration, chilled-water/glycol cooling coils, or chemical dehumidification is used. Chemical dehumidification is rarely used in semiconductor facilities because of the high maintenance cost and potential for chemical contamination in the cleanroom. Although an operating cleanroom generally does not require reheat, systems are typically designed to provide heat to the space when new cleanrooms are being built and no production equipment has been installed.

Makeup air is humidified by steam humidifiers or atomizing equipment. Steam humidifiers are most commonly used. Take care to avoid releasing water treatment chemicals. Stainless-steel unitary packaged boilers with high-purity water and stainless-steel piping have also been used. Water sprayers in the cleanroom return use air-operated water jet sprayers. Evaporative coolers can take advantage of the sensible cooling effect in dry climates.

Pressurization

Pressurizing semiconductor cleanrooms is another method of contamination control, providing resistance to infiltration of external sources of contaminants. Nearby particulate contaminants enter the cleanroom by infiltration through doors, cracks, pass-throughs, and other penetrations for pipes, ducts, etc. The cleanest cleanroom should have the highest pressure, with decreasing pressure corresponding to decreasing cleanliness. A differential pressure around 0.05 in. of water is often used.

For small semiconductor cleanrooms or clean zones in Classes 100,000 and 10,000 (ISO Classes 8 and 9), ceiling supply and low sidewall return is a typical airflow arrangement. The primary air system alone can handle the internal cooling load and the required room air change rate. Pressurization system designs are very similar to those in pharmaceutical facilities.

For cleaner (Class 1000/ISO Class 7 and cleaner) semiconductor classrooms, primary/secondary air systems are common. The secondary (makeup) HVAC unit takes care of the outside air and internal cooling loads, and the primary (recirculating) unit delivers the required room air change rate, and additional cooling if needed. A raised, perforated floor return is common for these classes. During balancing, manual or automatic balance dampers are usually set at fixed positions at air supply, return, and exhaust systems.

In vertical- and unidirectional-flow cleanrooms, single-stage constant volume for supply and return flows is common. Because internal dust generation from people and process could be lower during nonoperating or unoccupied mode than operating or occupied mode, using multiple recirculating blowers to create two- or multiple-stage supply and return flow rates is feasible as long as the room cleanliness meets the designated classification at all times, validated through continuous particle count measurement. In the nonoperating or unoccupied mode, reduced levels of supply and return airflow rates should also ensure maintaining proper room pressurization level.

Pressure level in the cleanroom is principally established by room airtightness and the offset flow value, which is the net flow among supply, exhaust, and return air rates. Process equipment exhaust rate is often determined by manufacturers' data, industrial hygienists, and codes. The design engineer should consult with the facility contamination control specialist to determine air change rates for each cleanroom.

One popular method of cleanroom pressurization is to fix the supply flow rate and adjust the return flow rate by volume dampers at return floor panels to create a specified positive room pressure. Return air to underfloor plenum or subfloor basement through perforated panels floor grilles or grates (usually with a 15 to 35% free area) can be balanced to ensure a fixed flow differential (offset flow) in the room. An adjustable, lockable balance damper normally is attached beneath the perforated floor panel or grate. When the damper is fully open, it normally imposes a pressure drop of 0.02 to 0.08 in. of water; higher pressure drop can be achieved when the dampers are turning toward the closed positions. Note that the balance damper could affect parallelism of the room's unidirectional flow.

Another method is to use variable-volume supply and return fans with volumetric flow tracing to ensure the required room pressure. This method could be a reasonable choice for a single, large cleanroom, but is not flexible enough to serve a suite with different room pressure requirements. For some industries, variable-volume systems may not be favorable; design engineers should consult with facility contamination control specialists before specifying variable-volume systems for cleanrooms.

Air locks typically are used between uncontrolled personnel corridors, entrance foyers, and the protective-clothing gowning area. Air locks may also be used between the gowning room and the main wafer fabrication area, and for process equipment staging areas before entering the wafer fabrication area. Install air locks only when they are really necessary, because their use along traffic paths could restrict personnel access and increase evacuation time during emergencies.

Commercial pressure differential sensors can reach accuracy at ±0.001 in. of water or better, and significant progress has been made on precision room pressure control. Many semiconductor processes affected by cleanroom pressure (e.g., glass deposition with saline gas) require process chamber pressure precision of ±0.00025 in. of water.

Sizing and Redundancy

Environmental HVAC design must consider future requirements of the factory. Semiconductor products can become obsolete in as little as two years, and process equipment may be replaced as new product designs dictate. As new processes are added or old ones removed (e.g., wet etch versus dry etch), the function of one cleanroom may change from high-humidity requirements to low, or the heat load many increase or decrease. Thus, the cleanroom designer must design for flexibility and growth. Unless specific process

equipment layouts are available, maximum cooling capability should be provided in all process areas at the time of installation, or space should be provided for future installations.

Because cleanroom space relative humidity must be held to close tolerances and humidity excursions cannot be tolerated, the latent load removal should be based on high ambient dew points and not on the high mean coincident dry-bulb/wet-bulb data.

In addition to proper equipment sizing, redundancy is also desirable when economics dictate it. Many semiconductor wafer facilities operate 24 h per day, seven days per week, and shut down only during holidays and scheduled nonworking times. Mechanical and electrical redundancy is required if loss of equipment would shut down critical and expensive manufacturing processes. For example, process exhaust fans must operate continuously for safety reasons, and particularly hazardous exhaust should have two fans, both running. Most process equipment is computer-controlled with interlocks to provide safety for personnel and products. Electrical redundancy or uninterruptible power supplies may be necessary to prevent costly downtime during power outages. Redundancy should be based on life-cycle economics.

ENERGY CONSERVATION IN CLEANROOMS

The major operating costs associated with a cleanroom include conditioning the air, fan energy for air movement in the cleanroom, and process exhaust. The combination of environmental conditioning and control, contamination control, and process equipment electrical loads can be as much as 300 W/ft^2. Besides process equipment electrical loads, most energy is used for cooling, air movement, and process liquid transport (i.e., deionized water and process cooling water pumping). A life-cycle cost analysis should be performed to determine design choices and their total cost of ownership over time.

Energy Metrics. To evaluate design options for HVAC systems in cleanrooms, it is convenient to compare overall efficiency using standard metrics. By using a metric such as airflow per kilowatt input, it is possible to compare system efficiency for different schemes. This is a good metric for air systems because it compares the amount of energy required to move a given quantity of air, and combines equipment efficiency as well as system effects. The owner can include this metric as a design criterion.

Similarly, metrics for chilled-water system performance in terms of kilowatts per ton can be established. Chiller performance and overall chilled-water system performance issues are well documented and should be consulted to set appropriate targets.

These various energy metrics highlight the wide variation in performance and the need to establish goals for system performance.

Fan Energy. Because airflow rates in cleanrooms can range from 4 to 100 times greater than in conventional HVAC, fan systems should be closely examined for ways to conserve energy. Static pressures and total airflow requirements should be designed to reduce operating costs. The fan energy required to move recirculation air may be decreased by reducing the air volume and/or static pressure. Energy conservation operating modes should be verified during system qualification. If these modes are not part of the original design, the control procedure must be changed and the operational change validated.

Air volumes may be lowered by decreasing recirculation airflow. This could allow decreasing HEPA or ULPA filter coverage or reducing cleanroom average air velocity. Reducing air volumes can yield significant savings. Based on a 90 fpm face velocity, each square foot reduction in filter coverage area in a room can save 25 to 50 W/ft^2 in fan energy and cooling load. Reducing room average velocity from 90 to 80 fpm saves 5 W/ft^2 in fan energy and in cooling energy. If the amount of air supplied to the cleanroom cannot be lowered, reducing static pressure can produce significant savings. With good fan selection and transport design, up to 15 W/ft^2 can be

saved per 1 in. of water reduction in static pressure. Installing low-pressure-drop HEPA filters, pressurized plenums in lieu of ducted filters, and proper fan inlets and outlets may reduce static pressure. Many cleanrooms operate for only one shift. Air volume may be reduced during nonworking hours by using two-speed motors, variable-frequency drives, inverters, inlet vanes, and variable-pitch fans, or, in multifan systems, by using only some of the fans.

Additional energy may be saved by installing high-efficiency motors on fans instead of standard-efficiency motors. Fan selection also affects energy cost. The choice of forward-curved centrifugal fans versus backward-inclined, airfoil, or vaneaxial fans affects efficiency. The number of fans used in a pressurized plenum design influences redundancy as well as total energy use. Fan size changes power requirements as well. Different options should be investigated.

Makeup and Exhaust Energy. Process exhaust requirements in the typical semiconductor facility vary from 1 to 10 cfm per square foot. Makeup air requirements vary correspondingly, with an added amount for leakage and pressurization. The energy required to supply the conditioned makeup air can be quite large. Careful attention to the layout and design of the makeup air system, especially minimizing system pressure drop and specifying efficient fans and motors, is important. The type of equipment installed normally determines the quantity of exhaust in a given facility. Heat recovery has been used effectively in process exhaust; when heat recovery is used, the heat exchanger material must be selected carefully because of the potentially corrosive atmosphere; requirements for nonhazardous cleanrooms are not as significant. Also, heat recovery equipment has the potential to cross-contaminate products in pharmaceutical facilities.

Makeup air cannot normally be reduced without decreasing process exhaust, which may be difficult to do because of safety and contamination control requirements. Therefore, the costs of conditioning the makeup air should be investigated. Conventional HVAC methods such as using high-efficiency chillers, good equipment selection, and precise control design can also save energy. One energy-saving method for large facilities uses multiple-temperature chillers to bring outdoor air temperature to a desired dew point in steps.

Cleanrooms and Resource Use: Opportunities to Improve Sustainability

Because of their highly specific and complex requirements, many cleanrooms have high energy and resource demands. When possible, designers and operators should look for opportunities to reduce these demands, not only for reasons of environmental health, but also for cost savings and avoidance of risk.

Cleanrooms are more complex than, for instance, a typical office building. When developing a cleanroom-driven project, using integrated design and construction can result in major rewards in cost, schedule, and operational efficiencies. Some of the most promising areas for energy and resource use reductions include the following:

- Optimize air distribution strategies and air change rates in clean areas; reducing air change rates saves on environmental conditioning energy, fan energy, equipment sizing, duct sizing, filter requirements (quantity, not quality), and equipment space.
- Analyze and evaluate process chemistry, including cleaning materials and methods. Reducing or eliminating VOC-based solvents, heavy metals, acids, etc., in processing reduces the need for dilution air, scrubbing, treatment of effluent and other environmental and life safety issues. This step must be integrated with process developers, operators, and regulatory compliance personnel to ensure that changes do not compromise final product quality and acceptance.
- Process equipment specifications should include performance criteria for support utility needs such as process water, com-

pressed air, exhaust air, and electrical power. More efficient equipment leads to savings in operational and capital costs. This approach may also prove attractive where process equipment is leased and will be returned to the equipment vendor, as is common in microelectronics, because of the processing technologies' rapid obsolescence. For the equipment or tool manufacturers, higher efficiency may enhance the toolset's resale value.

The effects of these broad areas of resource use reduction and energy savings on building systems should be obvious; however, there are other tangible benefits that should be considered. Reducing the resource use or environmental footprint of the cleanroom extends the site infrastructure's carrying capacity. On developed sites in developed areas, this can save significant capital and operational costs by reducing the need to increase the site's capacity or infrastructure to handle an additional building or operation. Reducing use of hazardous, toxic, or noxious materials can reduce the owner's exposure to environmental health and safety risks and the need to treat discharge air and water streams.

NOISE AND VIBRATION CONTROL

Noise is difficult to control. Noise generated by contamination control equipment requires particular attention, although production equipment noise may be more significant than HVAC noise. Before beginning design, noise and vibration criteria should be established. Chapter 47 provides more complete information on sound control.

In normal applications of microelectronics contamination control, equipment vibration displacement levels need not be dampened below 0.5 μm in the 1 to 50 Hz range. However, electron microscopes and other ultrasensitive microelectronics cleanroom instruments may require smaller deflections in different frequency ranges. Photolithographic areas may prohibit floor deflections greater than 0.075 μm. As a general rule, displacement should not exceed one-tenth the line width.

For highly critical areas, consider using vaneaxial fans. These fans generate less noise in lower frequencies, and can be dynamically balanced to displacements of less than 4 μm, which decreases the likelihood of transmitting vibration to sensitive areas in electronics cleanrooms.

ROOM CONSTRUCTION AND OPERATION

Control of particulate contamination from sources other than the supply air depends on the classification of the space, the type of system, and the operation involved. Typical details that may vary with the room class include the following:

Construction Finishes
- **General.** Smooth, monolithic, cleanable, and chip-resistant, with minimum seams, joints, and no crevices or moldings
- **Floors.** Sheet vinyl, epoxy, or polyester coating with wall base carried up, or raised floor (where approved) with and without perforations using the previously mentioned materials
- **Walls.** Plastic, epoxy-coated drywall, baked enamel, polyester, or porcelain with minimum projections
- **Ceilings.** Plaster covered with plastic, epoxy, or polyester coating or with plastic-finished clipped acoustical tiles (no tiles in pharmaceutical cleanrooms) when entire ceiling is not fully HEPA- or ULPA-filtered
- **Lights.** Teardrop-shaped single lamp fixtures mounted between filters, or flush-mounted and sealed
- **Service penetrations.** All penetrations for pipes, ducts, conduit runs, etc., fully sealed or gasketed
- **Appurtenances.** All doors, vision panels, switches, clocks, etc., either flush-mounted or with sloped tops

- **Windows.** All windows flush with wall; no ledges on cleanest side

Personnel and Garments
- Hands and face cleaned before entering area
- Lotions and soap containing lanolin to lessen shedding of skin particles
- No cosmetics and skin medications
- No smoking or eating
- Lint-free smocks, coveralls, gloves, head covers, and shoe covers

Materials and Equipment
- Equipment and materials are cleaned before entry.
- Nonshedding paper and ballpoint pens are used. Pencils and erasers are not permitted.
- Work parts are handled with gloved hands, finger cots, tweezers, and other methods to avoid transfer of skin oils and particles.
- Sterile pharmaceutical product containers must be handled with sterilized tools only.

Particulate Producing Operations
- Electronics grinding, welding, and soldering operations are shielded and exhausted.
- Nonshedding containers and pallets are used for transfer and storage of materials.

Entries
- Air locks and pass-throughs maintain pressure differentials and reduce contamination.

INTEGRATION OF CLEANROOM DESIGN AND CONSTRUCTION

Integrated design and construction addresses all stages and aspects of cleanroom construction, to achieve better-quality, faster delivery; lower-cost, more optimized operation and maintenance; lower energy consumption; a cleaner environment; safer, more reliable, and more productive conditions; and longer service life. Integrated building design (IBD) is discussed in detail in Chapter 57.

A complete cleanroom project usually includes the following stages (see Figure 14): development of scope, budget, and overall project execution plan; predesign, conceptual, and schematic design; preliminary, final design, and construction documentation; and construction service.

Although the entire cleanroom building project is a large and complex operation, it may be simplified if it is considered as an integrated system with a unified overall scope of work and timeline to be achieved by an integrated design and construction team. In an integrated approach, all individual systems and their components are considered as subsystems of the overall integrated cleanroom building project, including the following:

- **Site/utilities:** overall site plan, entrances and gates, roads and transportation, landscape, electrical substations or electrical main connection, gas or other fuel main intake pressure regulation station, water, sewer, sanitary and storm drain piping and main connections, telephone, network, security and fire protection system main connections, outdoor lighting, etc.
- **Building:** foundations, structure system, walls, roofs, ceilings, floors, elevators, electrical, gas, fuel, water, sewer, plumbing, sanitary, mechanical, HVAC, chiller, boiler, noise control, lighting, process systems, energy and process material recovery systems, exhaust air and wastewater treatment systems, hazard control systems, explosion- and corrosionproofing, instrumentation and control systems, fire protection systems, etc.
- **Cleanroom:** walls; roofs; ceilings; HEPA or ULPA filters; floors; mini-clean environment; clean tunnels; clean booths; recirculating air, makeup air, and exhaust air systems; lighting, process
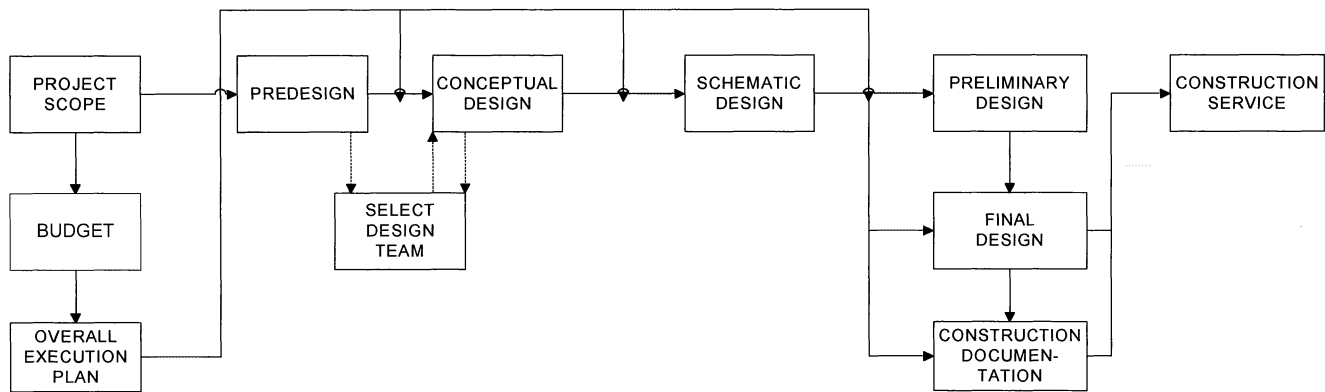
Fig. 14 General Design and Construction Procedure

mechanical, chemical, electrical, and control systems; production lines; process conveyers, special gas supply systems; acoustics; operating personnel, material, and products access doors, windows, or openings; air showers; room temperature, humidity, static electricity, CO_2, pressurization, and cleanliness monitoring and control systems; fire protection and after-fire recovery systems; seismic design, emergency response facilities, etc.

- **Implementation:** construction, installation work, system start-up, test and adjustment, balancing, commissioning, and handover.
- **Building management:** system operation and maintenance.

Figure 12 shows an example of how an HVAC fan deck and related electrical and control systems integrated into the building structure level. In a recent semiconductor plan, the mechanical room was used as the housing for makeup air units.

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IEST-RP-CC005	Gloves and finger cots used in cleanrooms and other controlled environments
IEST-RP-C-006.2	Testing cleanrooms
IEST-RP-CC007.1	Testing ULPA filters
IEST-RP CC008	Gas-phase adsorber cells

IEST-RP-CC009.2	Compendium of standards, practices, methods, and similar documents relating to contamination control
IEST-RP-CC011.2	A glossary of terms and definitions relating to contamination control
IEST-RP-CC012.1	Considerations in cleanroom design
IEST-RP-CC013	Equipment calibration or validation procedures
IEST-RP-CC014	Calibrating particle counters
IEST-RP-CC015	Cleanroom production and support equipment
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IEST-RP-CC019	Qualifications for agencies and personnel engaged in the testing and certification of cleanrooms and clean air devices
IEST-RP-CC020	Substrates and forms for documentation in cleanrooms
IEST-RP-CC021	Testing HEPA and ULPA filter media
IEST-RP-CC022.1	Electrostatic charge in cleanrooms and other controlled environments
IEST-RP-CC023.1	Microorganisms in cleanrooms
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CHAPTER 17

DATA PROCESSING AND ELECTRONIC OFFICE AREAS

DATACOM (data processing and telecommunications) facilities are predominantly occupied by computers, networking equipment, electronic equipment, and peripherals. The most defining HVAC characteristic of data and communications equipment centers is the potential for exceptionally high sensible heat loads (often orders of magnitude greater than a typical office building). In addition, the equipment installed in these facilities typically:

- Serves mission-critical applications (i.e., continuous operation)
- Has special environmental requirements (temperature, humidity, and cleanliness)
- Has the potential for disruptive overheating and equipment failure caused by loss of cooling

Design of any datacom facility should also address the fact that most datacom equipment will be replaced at least once with more current technology during the life of the facility. As described in *Datacom Equipment Power Trends and Cooling Applications* (ASHRAE 2005a), typical datacom equipment product cycles are 1 to 5 years, whereas facilities and infrastructure have life cycles of 10 to 25 years. Replacement equipment has historically required more demanding power and cooling requirements.

Understanding these critical parameters is essential to datacom facility design.

DESIGN CRITERIA

Types of datacom (ASHRAE 2005a) equipment that require air conditioning to maintain proper environmental conditions include

- Compute servers (2U and greater)
- Compute servers (1U, blade, and custom)
- Communication (High-density)
- Communication (Extreme-density)
- Tape storage
- Storage servers
- Workstations (standalone)
- Other rack- and cabinet-mounted equipment

Personnel also occupy datacom facilities, but their occupancy is typically transient and environmental conditions are more typically dictated by equipment needs. However, human occupancy in smaller datacom facilities may influence the ventilation air quantity.

Overview

Environmental requirements of datacom equipment vary depending on the type of equipment and/or manufacturer. However, a consortium of manufacturers has agreed on a set of four standardized conditions (Classes 1 to 4), listed in *Thermal Guidelines for Data Processing Environments* (ASHRAE 2004). A fifth classification,

the Network Equipment—Building Systems (NEBS) class, is typically used in telecommunications.

- **Class 1:** typically a datacom facility with tightly controlled environmental parameters (dew point, temperature, and relative humidity) and mission-critical operations; types of products typically designed for this environment are enterprise servers and storage products.
- **Class 2:** typically a datacom space or office or lab environment with some control of environmental parameters (dew point, temperature, and relative humidity); types of products typically designed for this environment are small servers, storage products, personal computers, and workstations.
- **Class 3:** typically an office, home, or transportable environment with little control of environmental parameters (temperature only); types of products typically designed for this environment are personal computers, workstations, laptops, and printers.
- **Class 4:** typically a point-of-sale or light industrial or factory environment with weather protection, sufficient winter heating, and ventilation; types of products typically designed for this environment are point-of-sale equipment, industrial controllers, or computers and handheld electronics such as PDAs.
- **NEBS:** per *Telcordia* (2001, 2002), and typically a telecommunications central office with some control of environmental parameters (dew point, temperature and relative humidity); types of products typically designed for this environment are switches, transport equipment, and routers.

Because Class 3 and 4 environments are not designed primarily for datacom equipment, they are not covered further in this chapter; refer to ASHRAE's (2004) *Thermal Guidelines for Data Center Environments* for further information.

Environmental Specifications

Table 1 lists recommended and allowable conditions for Class 1, Class 2, and NEBS environments, as defined by the footnoted sources. Figure 1A shows recommended temperature and humidity conditions for these classes on a psychrometric chart, and Figure 1B shows allowable temperature and humidity conditions. Note that dew-point temperature and relative humidity are also specified.

Air density also affects the ability of datacom equipment to be adequately cooled. ASHRAE's (2004) *Thermal Guidelines for Data Processing Environments* suggests that data center products be designed to operate up to 10,000 ft altitude, but recognizes that there is reduced mass flow and convective heat transfer associated with lower air density at higher elevations. To account for this effect, the guideline includes a derating chart for the maximum allowable temperature of 1°F per 550 ft altitude above 2950 ft (Classes 1 to 4). Figure 2 shows the altitude derating recommended by ASHRAE (2004) for Classes 1 and 2, and for NEBS.

The stated environmental conditions are as measured at the inlet to the data and communications equipment, and not average space or return air conditions.

The preparation of this chapter is assigned to TC 9.9, Mission Critical Facilities, Technology Spaces, and Electronic Equipment.
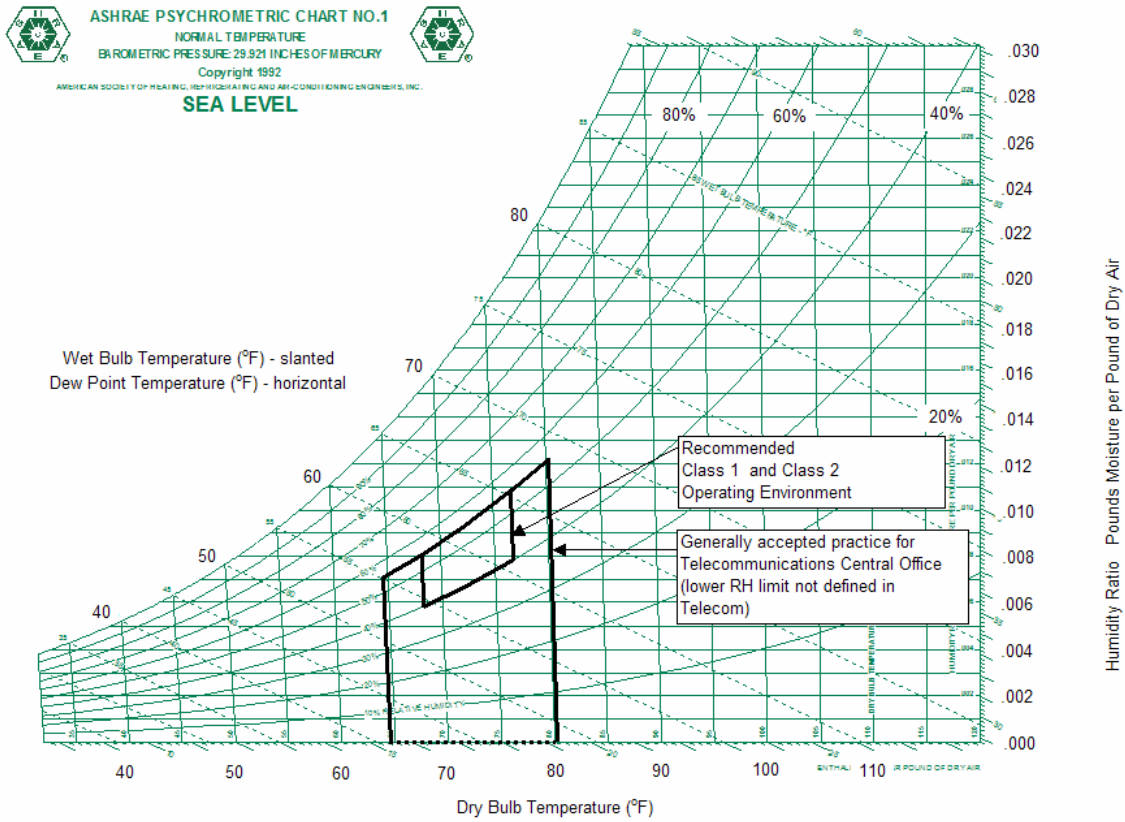
Fig. 1A   Recommended Data Center Class 1, Class 2, and NEBS Operating Conditions
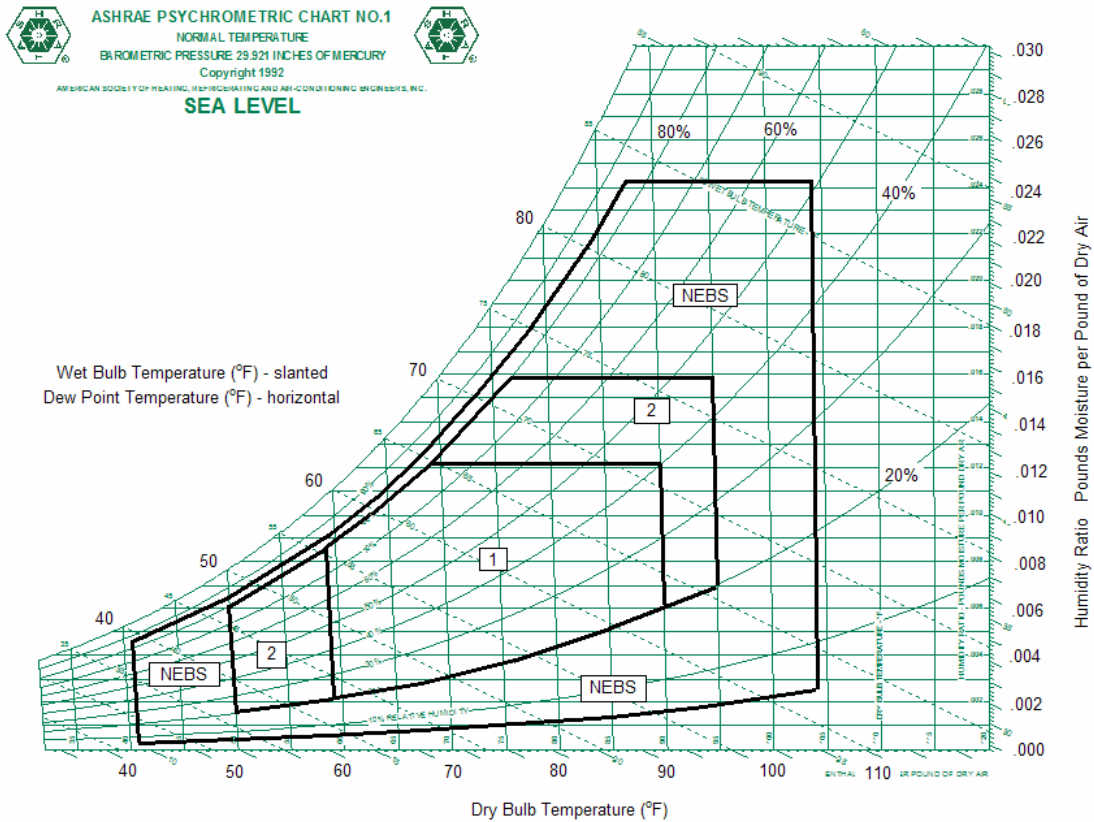
Fig. 1B   Recommended Data Center Class 1, Class 2, and NEBS Operating Conditions

Table 1 Class 1, Class 2, and Selected NEBS Design Conditions

| Condition | Classes 1 and 2 | | NEBS | |
	Allowable Level	Recommended Level	Allowable Level	Recommended Level
Temperature control range	59 to 90°F[a,f] (Class 1) 50 to 95°F[a,f] (Class 2)	68 to 77°F[a]	41 to 104°F[c,f]	65 to 80°F[d]
Maximum temperature rate of change	9°F/h[a]		54°F/h[a,c] 173°F/h[a,d]	
Relative humidity control range	20 to 80%, 3°F max. dew point[a] (Class 1) 70°F max. dew point[a] (Class 2) [e]	40 to 55%[a]	5 to 85%, 82°F max. dew point[c]	Max 55%
Filtration quality	65%, min. 30% (MERV 11, min. MERV 8)[b]			Min. 85% (Min. MERV 13)[b]

[a]Inlet conditions recommended in ASHRAE (2004).
[b]Percentage values per ASHRAE *Standard* 52.1 dust-spot efficiency test. MERV values per ASHRAE *Standard* 52.2.
[c]*Telcordia* (2002).
[d]*Telcordia* (2001).

[e]Generally accepted telecommunications practice. Telecommunications central offices are not generally humidified, but personnel are often grounded to reduce electrostatic discharge (ESD).
[f]See Figure 2 for temperature derating with altitude.
[g]*Telcordia* recommendation.
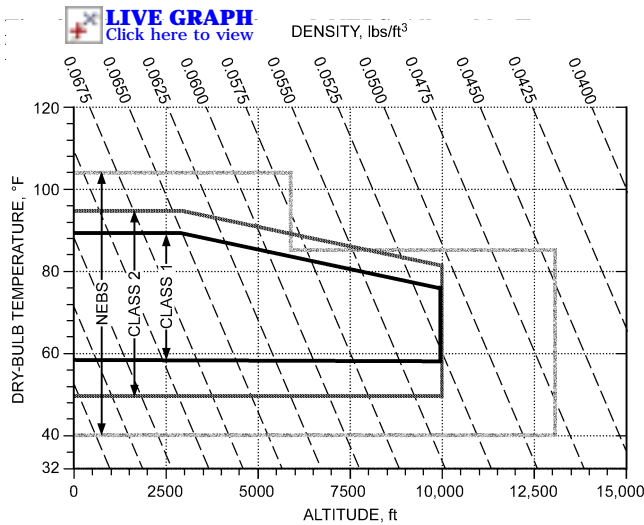
Fig. 2 Class 1, Class 2, and NEBS Allowable Temperature Range Versus Altitude

Temperature

Equipment exposed to prolonged high temperature, or to high temperature gradients, can experience thermal shutdown. Required inlet air conditions to datacom equipment should be checked for all equipment, but a typical recommended range is 68 to 77°F. For telecommunications central offices and NEBS, the ranges are wider (see Table 1). The recommended range for telecommunication and central offices is 65 to 80°F (*Telcordia* 2001).

Operation in the allowable range should usually be considered acceptable for short periods of time. However, facility designers and operators should strive for continuous operation in the recommended range.

Not only is air temperature into the electronics critical for reliable operation of components in the electronic box, but the air discharged from the electronics and flowing over the components (cabling, connectors, etc.) at the exit must also be addressed.

Temperature Rate of Change

Some datacom manufacturers have established criteria for allowable rates of environmental change to prevent shock to the data and communications equipment. These criteria need to be reviewed for all installed datacom equipment. A maximum inlet temperature change of 9°F/h is recommended by ASHRAE (2004a) for Classes 1 and 2. Humidity rate of change is typically most important for tape and storage products. Typical requirements for tape are a rate of change of less than 3.5°F/h and a relative humidity change of less than 5%/h (ASHRAE 2004).

In telecommunications central offices, the NEBS requirement per *Telcordia* (2001) for testing new equipment is a rate change of 54°F/h. However, in the event of an air-conditioning failure, the rate of temperature change can easily be significantly higher. Consequently, *Telcordia* (2001) recommends additional equipment testing with a gradient of 173°F/h for 15 min. Manufacturers' requirements should be reviewed and fulfilled to ensure that the system functions properly during normal operation and during start-up and shutdown.

Procedures must be in place for response to an event that shuts down critical cooling systems while critical loads continue to operate, causing the space temperature to begin rising immediately. Procedures should also be in place governing how quickly elevated space temperatures can be returned to normal to avoid thermal shock damage.

Datacom equipment usually tolerates a somewhat wider range of environmental conditions when not in use (see Table 2.1 in ASHRAE, 2004). However, it may be desirable to provide uninterruptible cooling in the room to maintain operating limits and minimize thermal shock to the equipment.

Humidity

High relative humidity may cause conductive anodic failures (CAF), hygroscopic dust failures (HDF), tape media errors and excessive wear, and corrosion. In extreme cases, condensation can occur on cold surfaces of liquid-cooled equipment. Low relative humidity may result in electrostatic discharge (ESD), which can destroy equipment or adversely affect operation. Tape products and media may have excessive errors when exposed to low relative humidity. In general, facilities should be designed and operated to maintain the recommended humidity range in Table 1, but excursions into the allowable range (more typically the equipment specification) should not significantly shorten equipment operating life.

Filtration and Contamination

Before being introduced into the data and communications equipment room, outside air should be filtered and preconditioned to remove particulates and corrosive gases. Table 1 contains both recommended and minimum filtration guidelines for recirculated air in a data center. Particulates can adversely affect data and communications equipment operation, so high-quality filtration and proper filter maintenance are essential. Corrosive gases can quickly destroy the thin metal films and conductors used in printed circuit boards, and corrosion can cause high resistance at terminal connection points. In addition, the accumulation of particulates on surfaces needed for heat removal (e.g., heat sink fins) can degrade

heat removal device performance. Further information on filtration and contamination in data centers can be found in Chapter 8 of *Design Considerations for Datacom Equipment Centers* (ASHRAE 2005b).

Ventilation

Data and communications equipment room air conditioning must provide adequate outside air to achieve two criteria:

- To maintain the room under positive pressure relative to surrounding spaces
- To satisfy ASHRAE *Standard* 62.1 requirements

The need for positive pressure to keep contaminants out of the room is usually the controlling design criterion in data and communication equipment rooms. Pressurization calculations can be performed using the procedures outlined in Chapter 27 of the 2005 *ASHRAE Handbook—Fundamentals*. Chapter 52 of this volume has calculation formulas for achieving pressurization as well as loss of pressure through cracks in walls and at windows.

Although most computer rooms have few occupants, calculations should always be performed to ensure that adequate ventilation for human occupancy is provided in accordance with ASHRAE *Standard* 62.1 and local codes. Internally generated contaminants may make the indoor air quality method the more appropriate procedure; however, maintaining positive pressure usually requires a higher outside airflow.

Envelope Considerations

In addition to meeting state, national, and local codes, there are several other parameters that should be considered in designing the envelope of datacom facilities, including pressurization, isolation, vapor retardants, sealing, and condensation.

- **Pressurization.** Datacom facilities are typically pressurized to prevent infiltration of air and pollutants through the building envelope. An air lock is recommended for a datacom equipment room door that opens directly to the outside. Excess pressurization with outside air should be avoided, because it makes swinging doors harder to use, and wastes energy through increased fan energy and coil loads.
- **Space Isolation.** Datacom equipment centers are usually isolated for both security and environmental control.
- **Vapor Retarders.** To maintain proper relative humidity in datacom facilities in otherwise unhumidified spaces, vapor retarders should be installed around the entire envelope. The retarder should be sufficient to restrain moisture migration during the maximum projected vapor pressure difference between datacom equipment room and the surrounding areas.
- **Sealing.** Cable and pipe entrances should be sealed and caulked with a vapor-retarding material. Doorjambs should fit tightly.
- **Condensation on exterior glazing.** For exterior walls in colder climates, windows should be double or triple-glazed and door seals specified to prevent condensation and infiltration. If possible, there should be no windows. If an existing building is used, windows should be covered.

Human Comfort

Human comfort is not specifically addressed in *Thermal Guidelines for Data Processing Environments* (ASHRAE 2004a) because the facilities typically have minimal and transient human occupancy. Although telecommunications central offices often have permanent staff working on the equipment, human comfort is not the main objective. Following the recommended Class 1 conditions (see Table 1) in a hot-aisle/cold-aisle configuration may result in comfort conditions that are cold in the cold aisle, and warm or even hot in the hot aisle. Personnel working in these spaces need to consider the temperature conditions that exist, and dress accordingly. If the hot aisle is excessively hot, portable spot-cooling should be provided. The National Institute for Occupational Safety and Health (NIOSH) provides detailed guidance on occupational exposure to hot environments (NIOSH 1986). Another concern is contact burns if equipment is too hot. Human tissue reaches the pain threshold at 111°F, and various levels of injury at levels above that (ASTM 2003). Take care that equipment surface temperatures do not represent a hazard.

Flexibility

As described in the introduction, technology is continually changing and datacom equipment in a given space is frequently changed and/or rearranged during the life of a datacom facility. As a result, the HVAC system serving the facility must be sufficiently flexible to allow plug-and-play rearrangement of components and expansion without excessive disruption of the production environment. In critical applications, it should be possible to modify the system without shutdown. If possible, the cooling system should be modular and designed to efficiently handle a wide range in heat loads.

Acoustics

Noise emissions in datacom facilities are the sum of datacom equipment noise and noise from the facility's HVAC equipment. The noise level of air-cooled datacom equipment has generally increased along with the power density and heat loads. Densely populated datacom facilities may run the risk of exceeding U.S. Occupational Safety and Health Administration (OSHA) noise limits (and thus potentially causing hearing damage without personnel protection); refer to the appropriate OSHA (1996) regulations and guidelines. European occupational noise limits are somewhat more stringent than OSHA's and are mandated in EC Directive 2003/10/EC (European Council 2003). Facility noise level calculations can be made following the methodology outlined in Chapter 47, and in Chapter 7 of the 2005 *ASHRAE Handbook—Fundamentals*. An acoustic consultant may be needed to properly predict sound levels from multiple sources and paths, as is typically the case in a datacom facility.

Manufacturers of electronic equipment typically take steps to minimize acoustic noise emissions from datacom equipment. Speed control of air-moving devices, rack- or frame-level acoustic treatments, and reduction of line-of-sight noise emissions are common techniques to reduce datacom equipment noise.

Vibration Isolation and Seismic Restraint

HVAC equipment in datacom facilities should be independently supported and isolated to prevent vibration transmission to the datacom equipment. If required, vibration isolators should be to be seismically rated for the specific environment into which they are installed, to comply with the appropriate codes. Consult datacom equipment manufacturers for equipment sound tolerance and specific requirements for vibration isolation. Many datacom equipment manufacturers test their equipment to the vibration and seismic requirements of *Telcordia* (2001). Additional guidance can be found in Chapter 54 and in the *International Building Code* (ICC 2006).

HVAC LOAD CONSIDERATIONS

HVAC loads in datacom facilities must be calculated in the same manner as for any other facility. Typical features of these facilities are a high internal sensible heat load from the datacom equipment itself and a correspondingly high sensible heat ratio. However, other loads exist and it is important that a composite load comprised of all sources is calculated early in the design phase, rather than relying on a generic overall "watts per square foot" estimate that neglects other potentially important loads.

Also, if the initial deployment or first-day datacom equipment load is low because of low equipment occupancy, the effect of the other loads (envelope, lighting, etc.) becomes proportionately more important in terms of part-load operation.

Datacom Equipment

The major heat source in datacom facilities is the datacom equipment itself. This heat can be highly concentrated, non-uniformly distributed, and variable. Equipment that generates large quantities of heat is normally configured with internal fans and airflow passages to transport cooling air, usually drawn from the space, through the equipment.

Information on datacom equipment heat release should be obtained from the manufacturer. Guidance on industry heat load trends can be obtained from ASHRAE's (2005a) *Datacom Equipment Power Trends and Cooling Applications*. It is important to know the approximate allocation of different types of datacom equipment when designing datacom facility environmental control, because heat loads of different types of equipment vary dramatically. Figure 3 shows projected trends of six equipment classifications through the year 2014; a sample heat load calculation based on these classifications is given in ASHRAE's (2005b) *Design Considerations for Datacom Equipment Centers*.

At the equipment level, ASHRAE (2004) includes a sample equipment thermal report that can provide heat release information in a format specifically suited for thermal design purposes. Nameplate information for data and communications equipment should not be used for thermal design, because it will yield unrealistically high design values and an oversized cooling system infrastructure.

Most current datacom equipment has variable-airflow cooling fans that depend on inlet temperature and/or load. Under typical operating conditions, the flow requirements of these fans may be low, but increase under extreme conditions such as high system inlet temperature. Consideration of this variable flow may be important to HVAC system design.

Load Considerations and Challenges

Similar to commercial loads, datacom loads often operate well below the calculated load. This can be more problematic for datacom facilities, though, because the load densities are so much greater than commercial installations. Further, the source of the load (datacom equipment) is often replaced at least once during the life of the cooling system, requiring consideration of oversized infrastructure or phased construction to accommodate future changes. The part- and low-load conditions must be well understood and equipment selected accordingly.

It is particularly important to understand initial and future loads in detail. Otherwise, the stated initial and future loads could have compounded safety factors or, in the worst cases, guesses. *Datacom Equipment Power Trends and Cooling Applications* (ASHRAE 2005a) identifies the following topics to consider when predicting future load:

- Existing applications' floor space
- Performance growth of technology based on footprint
- Processing capability compared to storage capability
- Change in applications over time
- Asset turnover

Once initial and future loads are understood, as well as the part- and low-load conditions, equipment can be selected. This includes gaining consensus from the project stakeholders regarding acceptable amount of disruption that can occur in an operating facility for upgrades such as cooling capacity or distribution.

Ventilation and Infiltration

For load calculation protocols relating to ventilation and infiltration, refer to Chapter 27 of the 2005 *ASHRAE Handbook—Fundamentals*.

Datacom facilities' outdoor air requirements may be lower than other facilities because of the light human occupancy load. In many cases, it is advantageous to precondition this air, with the space under positive pressure, to allow for 100% sensible cooling in the space. If this approach is adopted, however, preconditioning system failure must also be addressed to avoid the potential for widespread condensation in the space.

Electrical Equipment

In some cases, power distribution units (PDUs) are located in the datacom equipment room as the final means of transforming voltage to a usable rating and distributing power to the datacom equipment. The heat dissipation from the transformers in the PDUs should be accounted for by referencing the manufacturer's equipment specifications.
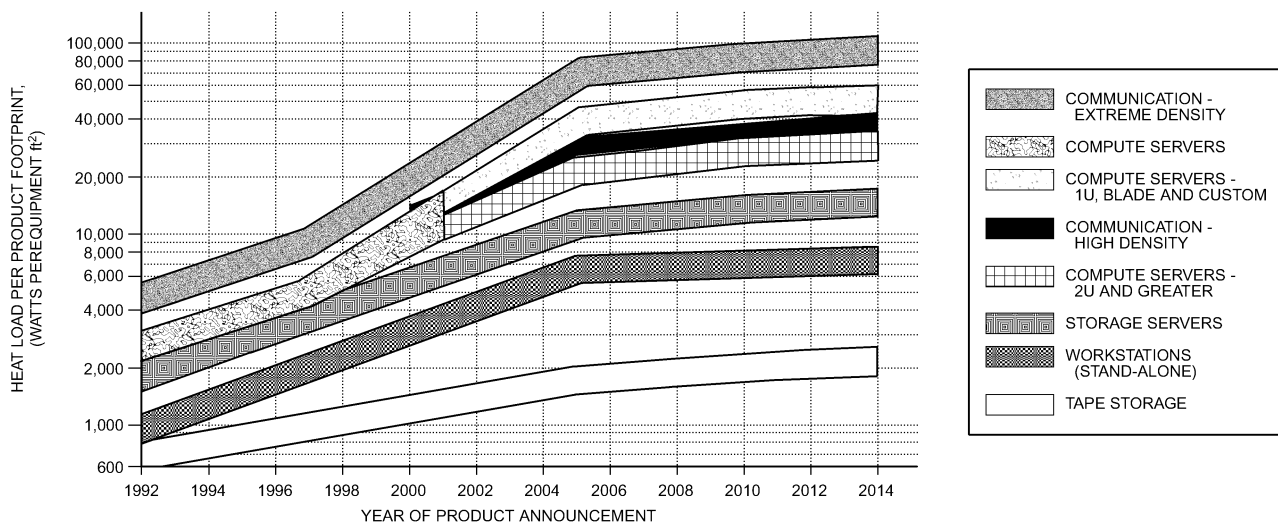
Fig. 3   Projected Power Trends of Datacom Equipment
(ASHRAE 2005a)

Lights

High-efficiency lighting should be encouraged, as well as lighting controls, to minimize lighting heat gain.

People

Occupancy loads should be considered as light work. People often comprise the only internal latent load in a datacom facility, which may be a factor in selecting cooling coils, especially if outdoor air is supplied through a dedicated outdoor air system.

Building Envelope

Heat gains through the building envelope depend on the buildings' location and construction type. More detailed design information on envelope cooling loads can be obtained from Chapter 30 of the 2005 *ASHRAE Handbook—Fundamentals*.

Heating and Reheat

The need for heat in electronic equipment-loaded portions of datacom facilities is typically minimal, because of the high internal heat gains in the spaces. Still, initial or first day loads in many datacom facilities can be low because of low equipment occupancy, so sufficient heating capacity to offset the outdoor air and envelope losses should be included in the design.

Many computer room air-conditioning (CRAC) units include reheat coils for humidity control. Reheat use for humidity control must be carefully monitored, because simultaneous heating and cooling wastes energy.

Humidification

Humidification and/or dehumidification is needed in most environments to meet both the recommended (40 to 55%) and allowable (20 to 80%) humidity ranges specified for Class 1 and Class 2 data centers (ASHRAE 2004a). In most cases, the predominant moisture load is outdoor air, but all potential loads should be considered. Where humidification is not provided, personal grounding is typically utilized to minimize electrostatic discharge (ESD) failures.

Vapor retardant analyses should also be performed where humidity-controlled spaces contain outside walls or ceilings. Refer to Chapter 25 of the 2005 *ASHRAE Handbook—Fundamentals* for additional design information.

High-Density Loads

Heat density of some types of datacom equipment is increasing dramatically. Stand-alone server heat loads (or rack loads) can have heat loads exceeding 30 kW. These increased heat densities require a design engineer to keep abreast of latest design techniques to ensure adequate cooling, and to pay close attention to the loads of installed electronic equipment and future equipment deployments.

Ensure that local high-density loads are provided with adequate local cooling, even when the overall heat density of the general space is below the high-density threshold. Rack inlet conditions should be checked and verified as adequate to meet the manufacturer's requirements. Refer to *Thermal Guidelines for Data Processing Environments* (ASHRAE 2004) for additional information and guidance.

Increases in heat density have made it more difficult to air-cool computers, which has led to increased interest in more efficient liquid-cooling techniques. Liquid cooling media include water, refrigerants, high-dielectric fluorocarbons, or two-phase fluids such as dielectrics. Some computer manufacturers have already taken this approach, and there are also products available that use liquid cooling at the cabinet level. The reader is encouraged to keep abreast of research and development in this area. ASHRAE (2006) has also published a book on liquid cooling, *Design Considerations for Liquid Cooling in Datacom and Telecommunications Rooms.*

New datacom facilities and those slated for major renovation should consider adding appropriate infrastructure (piping taps, feeders, etc.) for future use and load increases. Retrofitting these "backbones" is typically much more expensive, disruptive, and risky.

Note that local high-density areas can have power densities significantly higher than the average for the center. Ideally, high-density computing equipment should be identified during design so appropriate cooling can be provided.

HVAC SYSTEMS AND COMPONENTS

It may be desirable for HVAC systems serving datacom facilities to be independent of other systems in the building, although cross-connection with other systems may be desirable for back-up. Redundant air-handling equipment is frequently used, normally with automatic operation. A complete air-handling system should provide ventilation, air filtration, cooling and dehumidification, humidification, and heating. Refrigeration systems should be independent of other systems and may be required year-round, depending on design.

Datacom equipment rooms can be conditioned with a wide variety of systems, including packaged computer room air-conditioning units and central-station air-handling systems. Air-handling and refrigeration equipment may be located either inside or outside datacom equipment rooms.

Computer Room Air-Conditioning (CRAC) Units

CRAC units are the most common datacom cooling solution. They are specifically designed for datacom equipment room applications and should be built and tested in accordance with the requirements of ANSI/ASHRAE *Standard* 127.

Cooling. CRAC units are available in several types of cooling system configurations, including chilled-water, direct expansion (DX) air-cooled, DX water-cooled, DX glycol-cooled, and dual-cooled (both chilled-water and DX). DX units typically have multiple refrigerant compressors with separate refrigeration circuits, air filters, and integrated control systems with remote monitoring panels and interfaces. Reheat coils and humidifiers are an option. Where weather conditions make this strategy economical, CRAC units may also be equipped with propylene glycol precooling coils and associated drycoolers to allow water-side economizer operation.

Location. CRAC units are usually located within the datacom equipment room, but may also be remotely located and ducted to the conditioned space. With either placement, their temperature and humidity sensors should be located to properly control inlet air conditions to the datacom equipment within specified tolerances (see Table 1). Analysis of airflow patterns in the datacom equipment room [e.g., with computational fluid dynamics (CFD)] may be required to optimally locate datacom equipment, CRAC units, and sensors, to ensure that sensors are not in a location that is not conditioned by the CRAC unit they control, or in a nonoptimum location that forces the cooling system to expend more energy than required.

Humidity Control. Types of available humidifiers within CRAC units may include steam, infrared, and ultrasonic. Consideration should be given to maintenance and reliability of humidifiers. It may be beneficial to relocate all humidification to a dedicated central system. Another consideration is that some humidification methods or improperly treated makeup water are more likely to carry fine particulates to the space.

Reheat is used in dehumidification mode when air is overcooled to remove moisture. On a call for reheat, sensible heat (typically from electric, hot-water, or steam coils) is introduced to supplement the actual load in the space. Using waste heat of compression (hot gas) for reheat may also be an energy-saving option. This overcooling and reheating should be tightly controlled.

Ventilation. Dedicated outdoor air systems have been installed in many datacom facilities to control space pressurization and humidity without humidifiers and reheat in either the CRAC units or
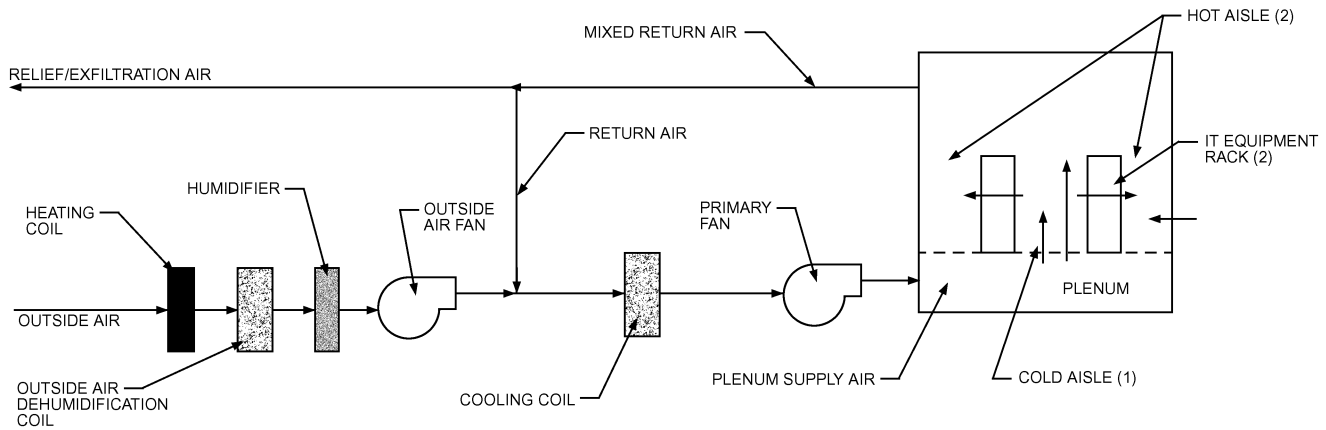
Fig. 4   Datacom Facility with Dedicated Outdoor Air Preconditioning

other datacom central cooling systems. Figure 4 shows an independent outdoor air preconditioning system in conjunction with a sensible-only recirculation system. The humidifier in the dedicated outdoor air system often controls the humidity in the datacom equipment room based on dew point.

Central-Station Air-Handling Units

Some larger datacom facilities and most telecommunications central offices use central-station air-handling units. Some of their advantages and disadvantages are discussed here.

Coil Selection and Control. A wide range of heating and cooling coil types can be used for datacom facilities, but, ideally, any coil design or specification should include modulating control. In addition, when dehumidifying, control of the cooling coil to maintain dew point can be critical to maintaining the datacom facility within temperature and humidity set points. For more information on cooling coil design, see Chapter 21 in the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*.

Humidification. Various types of central-station humidification systems can be used for datacom facility applications, with each type offering varying steam quality, level of control, and energy consumption. Available water quality and requirements for water treatment must also be considered when selecting the humidifier type.

Flexibility and Redundancy using VAV Systems. Flexibility and redundancy can be achieved by using variable-volume air distribution, oversizing, cross-connecting multiple systems, or providing standby equipment. Compared to constant-air-volume units (CAV), variable-air-volume (VAV) equipment can be sized to provide excess capacity but operate at discharge temperatures or airflow rates appropriate for optimum temperature and humidity control, reducing operational fan power requirements and the need for reheat.

Common pitfalls of VAV include shifts in underfloor pressure distribution and associated flow through tiles. Airflow should be modeled using CFD or other analytical techniques to ensure that the system can modulate without adversely affecting overall airflow and cooling capability to critical areas.

Chilled-Water Distribution Systems

Chilled-water distribution systems should be designed to the same standards of quality, reliability, and flexibility as other computer room support systems. Where growth is likely, the chilled-water system should be designed for expansion or addition of new equipment without extensive or disruptive shutdown. Figure 5 illustrates a looped chilled-water system with sectional valves and
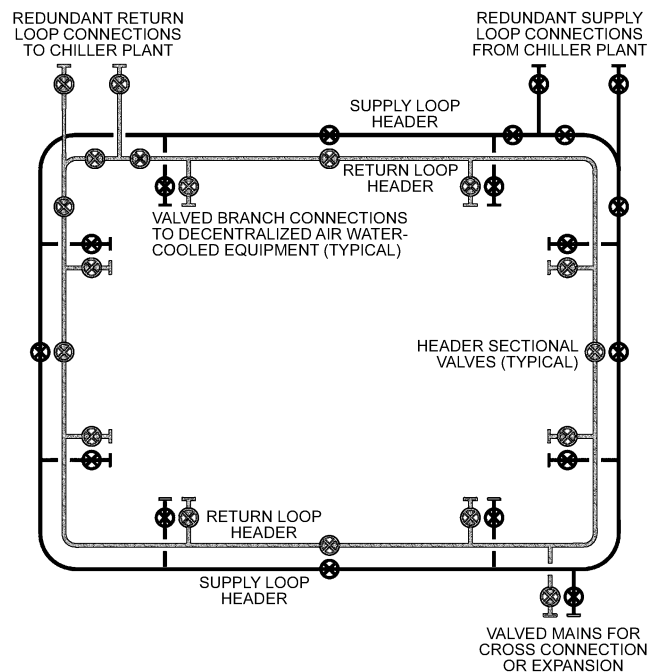
Fig. 5   Chilled-Water Loop Distribution

multiple valved branch connections. The branches could serve air handlers or water-cooled computer equipment.

The valve quantity and locations allow modifications or repairs without complete shutdown because chilled water can be fed from either side of the loop. This loop arrangement is a practical method of improving the reliability of a chilled-water system serving a computer room. "Future taps" should have blind flanges with a pressure gage and drain between the flange and isolation valve to allow the valve to be exercised and checked for holding performance. Sectional valves should be suitable for bidirectional flow and tight shutoff from flow in either direction, to allow maintenance on either side of the valve. In some cases, multiple valves may be required to allow maintenance of the valves themselves.

Where chilled water serves CRAC units or other packaged equipment in the datacom equipment room, select water temperatures that satisfy the space sensible cooling loads without causing latent cooling. Because datacom equipment room loads are primarily sensible, chilled-water supply temperature can be higher than in commercial applications. Greater differentials between the

supply and return chilled-water temperatures allow reduced chilled-water flow, which saves pump energy and piping installed costs.

To provide better temperature control of datacom equipment in a data center, numerous manufacturers offer products where liquid (water or refrigerant) is brought close to the datacom rack and used to remove the heat generated by the datacom equipment. Liquid-cooled heat exchangers placed in strategic locations are used to cool hot air exhausted from the datacom equipment, thereby removing either all or part of the equipment's heat load.

Chilled-water pipe insulation with a vapor barrier is required to prevent condensation, but not to prevent thermal loss in a cold plenum; therefore, minimum insulation thickness should be considered, because insulated piping can restrict underfloor air distribution.

Condenser Systems

Heat rejection in datacom facilities can be with either water-cooled or air-cooled systems. Basic information on condenser water systems can be obtained from Chapter 13 in the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*. Where evaporative cooling or open-cell cooling towers are used, consider using makeup water storage as a back-up to the domestic water supply (which provides condenser makeup water).

The "dry-cooler" system incorporates a closed glycol piping loop, which transfers heat from a unit-mounted condenser to an outdoor-air-to-glycol heat exchanger. The same glycol loop is sometimes attached to an economizer cooling coil, installed in the airstream of the CRAC unit, which allows for partial free cooling when the glycol loop temperature is below the unit's return air temperature.

Air-cooled systems generally support CRAC units with built-in refrigeration compressors and evaporating coils. These systems reject heat to remote air-cooled refrigerant condensers. Air-cooled and dry-cooler systems eliminate the need for makeup water systems (and back-up makeup water systems). Cooling towers, dry coolers, etc., need the same level of redundancy and diversity required of the chillers and other critical infrastructure.

Air-Conditioning Systems

Air-conditioning systems should be designed to match the anticipated cooling load and be capable of expansion if necessary; year-round, continuous operation may be required. Expansion of air-conditioning systems while maintaining continuous operation of the data center may also be necessary. A separate system for datacom equipment room(s) may be desirable where system requirements differ from those provided for other building and process systems, or where emergency power requirements preclude combined systems.

Heat recovery chillers may provide an efficient means to recover and reuse heat from datacom equipment environments for comfort heating of typical office environments. The system must provide the reliability and redundancy to match the facility's needs. System operation, servicing, and maintenance should not interfere with facility operation.

Chillers

Because datacom facilities often use large quantities of energy, cooling systems should be designed to maximize efficiency. For many facilities, water-cooled chillers are likely the most efficient system. Basic information on chillers can be obtained from Chapter 38 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*.

Part-load efficiency should also be considered during chiller selection, because data centers often operate at less than peak capacity. Chillers with variable-frequency drives, high evaporator temperatures, and low entering condenser water temperatures can have part-load operating efficiencies of 0.35 kW/ton or less. The relative

energy efficiency of primary versus secondary pumping systems should also be analyzed to optimize energy consumption.

Heat recovery chillers may be an efficient way to recover heat from datacom equipment environments for use in other applications. The heat recovery system must provide the reliability and redundancy needed by the facility. System operation, servicing, and maintenance should not interfere with facility operation.

Pumps

Pumps and pumping system design should take into account energy efficiency, reliability and redundancy. It may be possible to design pumps with variable-speed drives, so that the redundant pump is always operational. Ramp-up to full speed occurs on a loss of an operating pump.

Basic information on pumps can be obtained from Chapter 39 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*, and piping systems are covered in Chapter 12 of that volume.

Piping

Chilled-water and glycol piping must be pressure-tested, fully insulated, and protected with an effective vapor retardant. The test pressure should be applied in increments to all sections of pipe in the computer area during construction. In new construction, piping is often installed in trenches below the raised floor to minimize its effect on air distribution. Typically, leak detection is provided along the piping path. When installed overhead, secondary containment is often provided for all piping in datacom equipment room or critical electrical support spaces. Secondary containment systems should incorporate leak detection capability, to detect condensation and identify leaks from damaged piping, valves, fittings, etc. Leak detection should also be placed wherever water piping passes through any critical space, regardless of pipe elevation.

Piping specialty considerations should include a good-quality strainer installed at the inlet to local cooling equipment to prevent control valve and heat exchanger passages from clogging. Strategically placed drains and vents must be included locally at all equipment. Thermometers and other sensors should be installed in a serviceable manner, such as in drywells. Pressure gages should include gage cocks.

If cross connections with other systems are made, the effect of introducing dirt, scale, or other impurities on datacom equipment room systems must be addressed.

Humidifiers

Many types of humidifiers may be used to serve datacom equipment areas, including steam-generating (remote or local), pan (with immersion elements or infrared lamps) and evaporative types (wetted pad and ultrasonic). Ultrasonic devices should use deionized water to prevent formation of abrasive dusts from crystallization of dissolved solids in the water. In general, care must be taken to ensure that particulates or chemicals corrosive to datacom equipment are not used.

The humidifier must be responsive to control, maintainable, and free of moisture carryover. The humidity sensor should be located to provide control of air inlet conditions to the equipment. For additional information, see Chapter 20 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*.

Controls and Monitoring

Controls. Control systems must be capable of reliable control of temperature, relative humidity, and, where required, pressurization within tolerance from set point. Control systems serving spaces requiring high availability must be designed so that component or communication failures do not result in failure of the controlled HVAC equipment.

There are a number of ways to accomplish this, but the general approach is to use multiple distributed control systems in a manner

such that no system can cause the failure of another system. Where required, HVAC components and their power supplies should have dedicated controllers installed to ensure automatic and independent operation of redundant HVAC systems in the event of failures.

Based on Table 1, control should be established that provides an inlet condition to data center equipment of 68 to 77°F and telecommunications equipment of 65 to 80°F. Care is needed to ensure that sensors are properly located and tuned, especially if converting from legacy control based on return air temperature. CFD analysis as well as control system simulation may be needed for a successful retrofit.

Where multiple packaged units are provided, regular calibration of controls may also be necessary to prevent individual units from working against each other. Errors in control system calibration, differences in unit set points, and sensor drift can cause multiple-unit installations to simultaneously heat and cool, and/or humidify and dehumidify, wasting a significant amount of energy. Also consider integrated control systems that communicate from unit to unit, sharing set points and sensor data to ensure coordination, and reduce the potential for units to work against each other. Lead/lag control could also be used, if desired.

Monitoring. Datacom facilities often require extensive monitoring of the mechanical and electrical systems. Multiple interface gateways are often used to interface different monitoring and control systems to the head-end monitoring system and ensure that failure of individual system communication components does not remove access to the total system information database.

Monitoring should include control system sensors as well as independent "monitoring-only" sensors and should include datacom equipment areas, critical infrastructure equipment rooms, command/network operations centers, etc., to ensure critical parameters are maintained. Monitoring also should be sufficient to ensure that anomalies are detected early and with adequate time to allow operating staff time to mitigate and restore conditions before equipment is affected. Monitored data can facilitate trending, alarming, and troubleshooting efforts.

Examples of suitable parameters for monitoring include underfloor static air pressure, temperature, and humidity; early-warning smoke detection; ground currents; and rack temperatures and humidity. Monitoring systems can be integral to or separate from control systems and can be as simple as portable data loggers or strip chart recorders or as complex as high-speed (GPS-synchronized) forensic time stamping of critical breakers and status points. New technologies allow distributed monitoring sensors to be connected to the data and communication network without separate wiring systems.

Because datacom equipment malfunctions may be caused by or attributed to improper control of the datacom room environmental conditions, it may be desirable to keep permanent records of the space temperature and humidity. Many datacom equipment manufacturers imbed temperature and humidity sensors in their equipment, which in turn can be correlated with equipment function and also provide for reduced-capacity operation or shutdown to avoid equipment damage from overheating. In the future it may be possible to connect IT sensors to building systems for monitoring and control.

As a minimum, alarms should be provided to signal when temperature or humidity limits are exceeded. Properly maintained and accurate differential pressure gages for air-handling equipment filters can help prevent loss of system airflow capacity and maintain design environmental conditions. All monitoring and alarm devices should provide local indication as well as interface to the central monitoring system.

AIR DISTRIBUTION

To provide effective cooling, air distribution should closely match load distribution. Distribution systems should be flexible enough to accommodate changes in the location and magnitude of

FRONT TO REAR (F-R) FRONT TO TOP (F-T) FRONT TO TOP AND REAR (F-T/R)
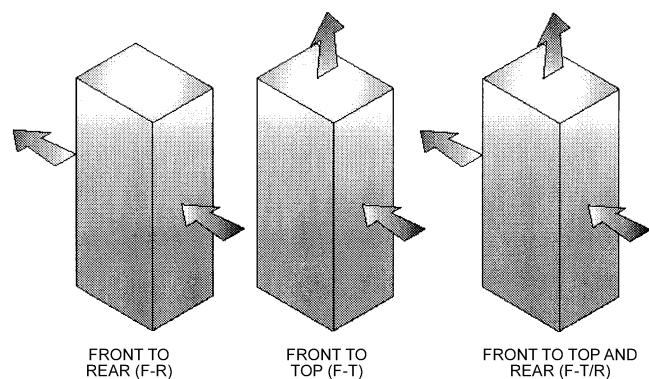
Fig. 6   Recommended Equipment Airflow Directivity

heat gains with minimal change in the basic distribution system. Distribution system materials should ensure a clean air supply. Duct or plenum material that may erode must be avoided. Access for cleaning is desirable.

Equipment Placement and Airflow Patterns

Datacom Equipment Airflow Protocols. Datacom equipment is typically mounted in racks or cabinets arranged in rows. In a typical configuration, the "front" of cabinets, racks, or frames (i.e., the side with the air inlets) faces one aisle, and the rear, which includes cable connections, faces another aisle. The cabinets or racks in a datacom environment are usually 78 in. high, whereas telecommunications frames are generally 72 to 84 in. high. Each cabinet or rack may contain a single piece of equipment, or it may contain any number of individual items of equipment, in sizes as small as 1U, where 1U = 1.75 in. (EIA *Standard* 310).

Supply air is drawn into the inlet of the datacom equipment cabinet or rack, picks up heat internal to the equipment, and is then discharged, typically from a different side of the equipment, eventually recirculating to the HVAC cooling coil, where the heat is rejected.

To cool datacom equipment efficiently and effectively, there needs to be complementary directivity for airflow through the equipment and airflow through the datacom equipment room. ASHRAE's *Thermal Guidelines for Data Processing Environments* (ASHRAE 2004) and *Telcordia* (2001) define recommended airflow protocols through datacom equipment. Figure 6 shows the three communications equipment airflow protocols that are recommended for use in datacom facilities. In the front-to-rear (F-R) protocol has cool air entering the front of the equipment rack (or cabinet), and exiting the rear. The F-T protocol has cool air entering the front of the equipment cabinet, and exiting the top, whereas the front-to-top-and-rear (F-T/R) protocol has cool air entering the front of the equipment, and exiting both the top and the rear. Rack-mounted equipment should follow the F-R protocol only; cabinet-mounted systems can follow any of the three shown.

Other airflow protocols for rack-mounted datacom equipment direct airflow through the left and/or right sides of the equipment within the rack. For these installations, airflow within the rack must be managed to ensure complementary directivity of airflow between independent shelves of data and communications equipment. In addition, spacing between adjacent racks in the same line-up of equipment must be adequate to ensure the appropriate segregation of hot exhaust and cold intake air streams.

Hot Aisle/Cold Aisle Configuration. Using alternating hot and cold aisles promotes separation of the cool supply and warm return streams which generally leads to lower equipment inlet temperatures and greater energy efficiency. Figure 7 shows a schematic view of a hot aisle/cold aisle configuration.
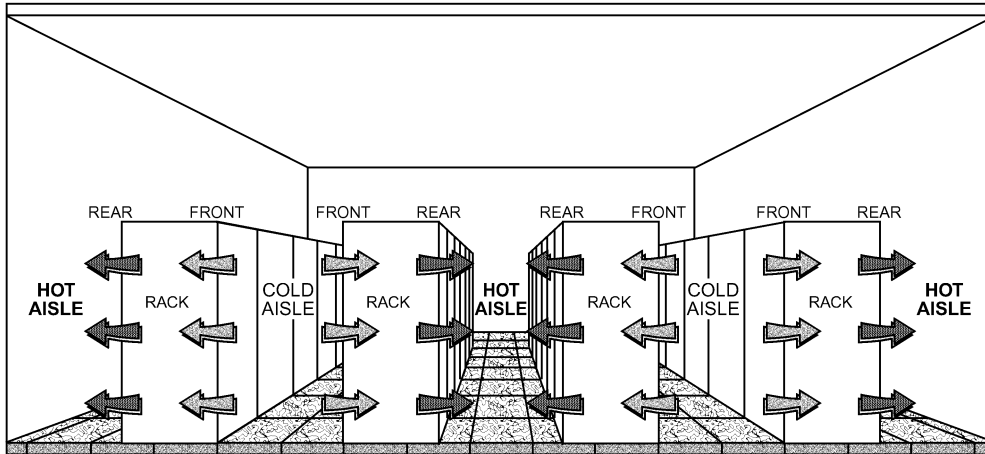
Fig. 7 Schematic of Hot-Aisle/Cold-Aisle Configuration
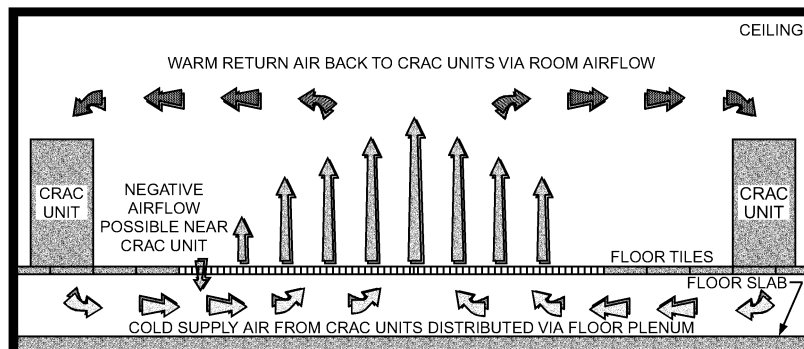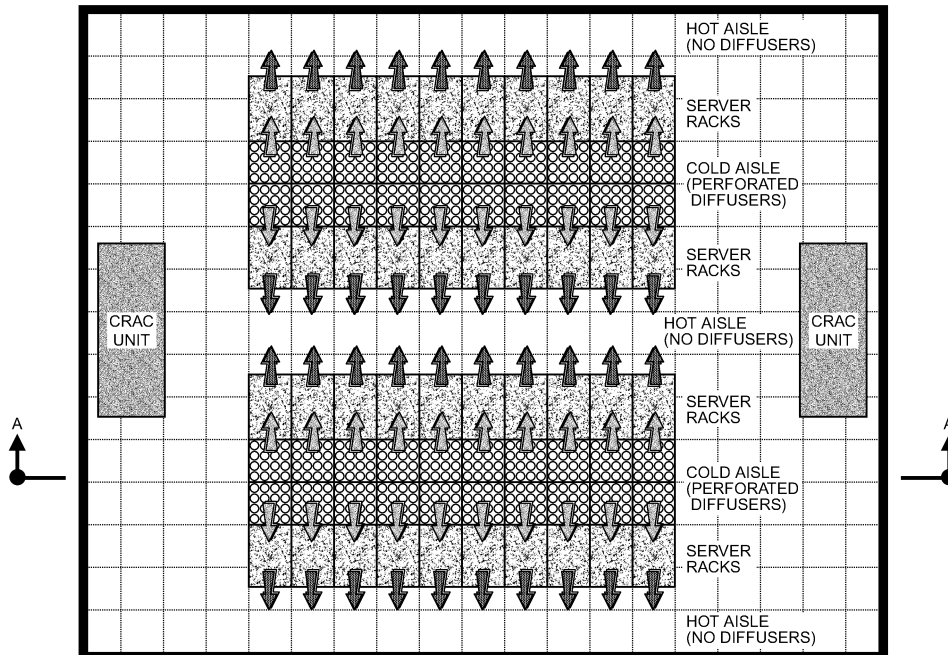
Fig. 8 Schematic of Datacom Equipment Room with Underfloor Plenum Supply Air Distribution

Underfloor Plenum Supply

Datacom facilities often use an underfloor plenum to supply cooling air to the equipment. As shown in Figure 8, the CRAC units push cold air into the plenum, from which it is introduced into data and communications equipment rooms via perforated floor tiles, tile cutouts, and other openings. The raised-floor design offers flexibility in placing computer equipment above the raised floor. Cooling air can, in theory, be delivered to any location simply by replacing a solid floor tile by a perforated tile.

With a hot-aisle/cold aisle configuration, perforated tiles are primarily placed in the cold aisle. Cooling air delivered by the perforated tiles is drawn into the front of the racks. Warm air is exhausted from the back of the racks into the hot aisle and is ultimately returned to the CRAC units.

Airflow Inlet Delivery Concerns. For good thermal management, required airflow must be supplied through the perforated tile(s) located near the inlet of each piece of datacom equipment. The heat load can vary significantly across datacom equipment rooms, and changes with addition or reconfiguration of hardware. For datacom equipment to operate reliably, the design must ensure that cooling air distributes properly (i.e., the distribution of airflow rates through perforated tiles matches the cooling air needs of equipment on the raised floor).

When adequate airflow is not supplied through the perforated tiles, internal fans in the equipment racks tend to draw air through the front of the cabinet from the path of least resistance, which typically includes the space to the sides of and above the racks. Because most of this air originates in the hot aisle, its temperature is high. Thus, cooling of the sides and upper portion of the equipment racks can be seriously compromised.

Air tends to stratify, with cold supply air near the floor and hot air near the ceiling, with a temperature gradient between. High discharge air velocity through floor tile or grates is necessary to displace warm air near the highest intakes. Floor grates can be useful, because of their high mass flow discharge rates.

Pressure Variations. Distribution of cooling airflow through perforated tiles is governed by the fluid mechanics of the space below the raised floor and not the large, visible, above-floor space. More specifically, the static pressure and air movement in the proportionately small underfloor space determines how much air flows through each perforated tile. Measurements from hundreds of datacom facilities confirm that flow rates from perforated tiles typically vary considerably, depending on their proximity to the CRAC unit.

Further, the pattern of airflow distribution is somewhat counterintuitive. More flow might be expected through tiles near the CRAC unit, and less away from it. In reality, there is typically very little flow near the CRAC, and greater flow through the perforated tiles located far away. Consequently, IT equipment placed near the CRAC often does not get much cooling air.

The flow rate through a perforated tile depends on the pressure difference across the tile (i.e., the difference between the plenum static pressure just below the tile and the room static pressure above the raised floor). Pressure variations in data and communications equipment rooms are generally small compared to the pressure drop across the perforated tiles. The tiles are fairly restrictive (e.g., 25% or less open area). When substantial numbers of tiles with greater open area are used, airflow through the tiles may also depend on airflow dynamics above the raised floor; CFD analysis or physical measurements may be required to ensure that a design meets equipment airflow requirements.

Under some conditions, nonuniformity of airflow distribution is so severe that perforated tile airflow is directed from the room down into the floor plenum. This effect is caused when most of the CRAC unit fan's total pressure is transformed into velocity pressure by high velocity in a relatively shallow underfloor plenum. This high-velocity underfloor air can create a localized negative pressure and induce small quantities of room air into the underfloor plenum. As distance from the supply fan increases, velocity decreases and the velocity pressure is converted to static pressure, which is required to produce airflow through perforated tiles or grates.

Other Factors Affecting Airflow Distribution. Other factors that influence distribution of airflow through perforated tiles include the following:

- Height of raised-floor plenum
- Percentage of open area of perforated tiles
- Location and size of leakage airflow paths
- Locations and redundancy of CRAC units
- Corresponding spreading of underfloor flow to various perforated tile locations
- Collision or merging of airstreams from different CRACs
- Flow disturbance caused by underfloor blockages such as pipes and cable trays

There is a common misconception that using more open tiles increases the airflow rate. Obviously, for the same static pressure in the plenum, more open tiles produce more airflow than more restrictive tiles. However, static pressure in the plenum cannot be assumed to be constant; it is a result of the tiles' flow resistance and other factors. The airflow rate is controlled by the amount of flow the CRAC unit blower is able to supply. For the blower, the controlling resistance is primarily internal to the CRAC unit, and the additional flow resistance offered by the perforated tiles is insignificant. Lowering perforated tile resistance typically does not significantly increase overall flow.

When very restrictive tiles (for example, 5% open) are used, their flow resistance can influence the flow delivered by the CRAC unit blower. In this case, plenum pressure becomes high enough that the blower operates at a new position on the fan curve. The need for very restrictive tiles should thus be avoided, if possible, although they could be necessary with low floor heights where the plenum is restricted and underfloor pressure distribution variation is high.

Using more restrictive tiles leads to a more uniform airflow distribution, but increases underfloor static pressure and may drive more airflow through leakage paths. Instead of using restrictive tiles everywhere, selective use of restrictive and open tiles in different locations can obtain the desired airflow distribution. To make flow distribution uniform, it is typically necessary to increase the percentage open area of tiles near the CRAC unit and to decrease it further away from the CRAC unit.

Finally, underfloor obstructions can cause significant airflow variations in the underfloor plenum. A raised-floor datacom facility usually contains pipes, cable trays, and structural columns. These obstructions disturb the airflow pattern under the floor, influence pressure distribution, and thus affect airflow coming out of the perforated tiles.

Because obstructions reduce the area available for flow, air velocity increases and leads to more significant pressure changes. Usually, static pressure increases on the upstream side of an obstruction and decreases on the downstream side, with the lowest static pressure at the point with highest velocity. Because of this effect, two adjacent perforated tiles located above an obstruction may yield very different airflow rates.

When redundant (standby) CRAC units are provided, air distribution in the datacom room changes depending on which units are operating.

Another consideration is the effect of dampers on the performance of perforated tiles and floor grates. Typically, dampers are two slotted metal plates installed on the bottom surface of a tile or grate, creating a plenum between the damper and discharge surface. Even in the full open position, there is a pressure drop across the damper, reducing static pressure across the discharge surface and resulting in lower air velocities than tiles or grates without dampers. Low discharge air velocity can cause problems in supplying cooling air to the highest rows of tall racks or cabinets.
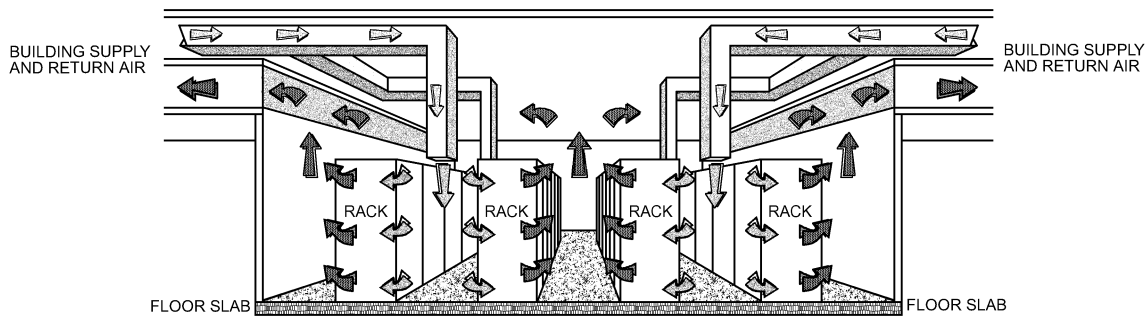
Fig. 9   Typical Ducted Ceiling Distribution Used in Datacom Facilities

Overhead and Ceiling Plenum Supply

As with an underfloor plenum supply, the hot-aisle/cold-aisle configuration should also be used with an overhead supply. Currently, overhead cooling methods are more typically found in telecommunications facilities.

Ducted Supply. Overhead ducted supply, shown in Figure 9, can be used in datacom facilities without a raised-floor plenum. The **vertical overhead (VOH)** system is currently the typical and preferred configuration of the large regional phone companies, although this might change to accommodate new technologies. This system can satisfy equipment and personnel comfort requirements, and can be fairly easily balanced to supply air to meet the distributed heat gain in the equipment room.

The vertical overhead supply system is typically limited to a cooling capacity of 130 W/ft^2 (*Telcordia* 2001) in mature telecommunications central offices, where the definition of watts per square foot is the average heat release of the datacom equipment in a 20 by 20 ft building bay. This limitation stems from the large physical duct sizes required near the ceiling. Air distribution is often affected by large overhead cabling installations.

Local and Supplemental Cooling Distribution. Recently, cooling systems have been developed in which small, modular cooling units are located close to the equipment racks, either within the rows of racks themselves, on top of racks, or mounted on the ceiling directly over a cluster of racks. An extreme example is a sealed rack system that provides its own cooling and has no heating effect on air inside the data center. Local cooling units may provide all the cooling for a data center or be used only in some (e.g., high-density).

Local cooling systems can be incorporated into new construction, and are also a good supplemental cooling approach to consider for retrofit applications where existing facilities lack sufficient infrastructure to expand their base cooling capacity. Supplemental cooling equipment may be located in or on a rack and include products that increase cool-air supply to a rack, capture hot-air exhaust from a rack, or partially cool air leaving the rack.

In designing and implementing local cooling, it is important to perform a thorough analysis to ensure that a cooling solution to one part of the facility does not create a problem in another part of the facility.

Other Overhead Cooling Strategies. Other cooling strategies are used, predominantly in telecommunications central offices. **Horizontal displacement (HDP)** air-distribution, mainly used in Europe and Asia, introduces air horizontally from one end of a cold aisle. A large volume of slightly cooled air moves along the aisle with low velocity. Subsequently, the electronic equipment draws necessary cold air from the cold aisle. However, this system requires more floor space to accommodate the displacement of the large diffusers.

Some long-distance carriers in North America use **horizontal overhead (HOH)** air distribution. This system introduces supply air horizontally above the cold aisles, and is generally used where raised floors are used for cabling.

Finally, **natural convection overhead (NOH)** air distribution, not commonly used, suspends cooling coils from the ceiling. Because the coils cool the hot air as it rises (because of buoyancy), there are no fans or ducting in this strategy.

For more information on different air-cooling strategies for telecommunications central offices, including cooling capacities, see *Telcordia* (2001).

Return Air

Return air paths discussed here can be used either with underfloor or overhead supply air systems. Most return air in datacom facilities is not ducted (i.e., heat discharged from datacom equipment enters the datacom equipment room at large and finds a pathway back to a large common return grille or to the inlet of a CRAC unit). This can be effective, but the opportunity for inefficiency, in some circumstances, is great because of potential short-circuiting and mixing of supply and return air. In addition, it is possible to draw hot equipment exhaust from one piece of equipment into the inlet of adjacent equipment. An example of how air can potentially short-circuit with an underfloor supply and unducted return configuration is highlighted in Figure 9.

Using ceiling plenums is an option for return air. Inlets should be located above hot aisles or datacom equipment with high heat dissipation to take advantage of the thermal plume created above the equipment. Ceiling plenum returns can capture part of the heat from data and communications equipment and lights directly in the return airstream. Assuming that the space is allowed to stratify, the return air being at a higher temperature than the average space temperature creates a higher temperature difference across the cooling coil, thereby allowing a reduction in airflow to the space.

Computational Fluid Dynamics Simulation

Air is the main carrier of heat and moisture in data centers. It is challenging but important to optimize the flow paths of both cold supply air and hot return to minimize mixing of these two streams as well as reduce any short-circuiting of cold air back to the air-conditioning systems.

Several factors affect airflow distribution and cooling performance of a data center. Physical measurements and field testing are not only time and labor intensive but sometimes impossible. In such a situation, computational fluid dynamics (CFD) simulations provide a feasible alternative for testing various design layouts and configurations in a relatively short time.

CFD simulations can, for example, predict air velocities, pressure, and temperature distribution in the entire data center facility; assess airflow patterns around racks and identify areas of recirculation; and provide a detailed cooling audit report for the facility, including performance evaluation of individual components such as air-conditioning units, racks, perforated tiles, and any other supplementary cooling systems in the facility.

Facilities managers, designers, and consultants can use these techniques to estimate performance of a proposed layout before

actually building the facility. Likewise, CFD simulations can provide appropriate insight and guidance in reconfiguring existing facilities optimize the cooling and air distribution system. For details on performing CFD, see Chapter 34 of the 2005 *ASHRAE Handbook—Fundamentals*.

ANCILLARY SPACES

Space must be allocated within a datacom facility for storing components and material, support equipment, and operating and servicing the datacom equipment. Some ancillary spaces may require environmental conditions comparable to those of the datacom equipment, whereas others may have less stringent requirements. Component and material storage areas often require environmental conditions comparable to those of the datacom equipment. Support equipment often has substantially less stringent environmental requirements, but its continuous operation is often vital to the facility's proper functioning.

Electrical Power Distribution and Conditioning Rooms

Electrical Power Distribution Equipment. Electrical power distribution equipment can typically tolerate more variation and a wider range of temperature and humidity than datacom equipment. Equipment in this category includes incoming service/distribution switchgear, switchboard, automatic transfer switches, panel boards, and transformers. Manufacturers' data should be checked to determine the amount of heat release and design conditions for satisfactory operation. Building codes should be checked to identify when equipment must be enclosed to prevent unauthorized access or housed in a separate room.

Uninterruptible power supplies (UPSs) come in various configurations, but most often use batteries as the energy storage medium. They are usually configured to provide redundancy for the central power buses, and typically operate continuously at less than full-load capacity. They must be air-conditioned with sufficient redundancy and diversity to provide an operable system throughout an emergency or accident. The relationship between load and heat release is usually nonlinear. Verification with the equipment vendor is necessary to properly size the HVAC system.

UPS power monitoring and conditioning (rectifier and inverter) equipment is usually the primary source of heat release. This equipment usually has self-contained cooling fans that draw intake air from floor level or the equipment face and discharge heated air at the top of the equipment. Air-distribution system design should take into account the position of the UPS air intakes and discharges.

Battery Rooms

Installation of secondary battery plants as a temporary back-up power source should be in accordance with NFPA *Standard* 70; IEEE *Standard* 1187 and other applicable standards should also be referenced, in addition to a design review with the local code official. Other relevant sources of guidance are NFPA *Standards* 70E and 76.

Most codes require 1 cfm/ft^2 of forced exhaust from a battery room when hydrogen detectors are not used. The exhaust fan(s) (typically ceiling-mounted) must run continuously. When hydrogen detectors are used, exhaust is also sized for 1 cfm/ft^2, but the fan(s) only need to run when hydrogen is detected.

Because of the potential high hazard associated with hydrogen gas build-up, battery room exhaust systems should be designed with redundancy and failure alarms. Best practice design includes both continuous fan operation and both "high" and "high-high" alarms in case one sensor goes out of calibration. If the system operates when hydrogen gas is detected, or if combustible concentrations of gas are expected, explosionproof motors and/or other provisions may be required to address an explosion hazard.

Nonsparking fan wheels may be required by code, and in any case are highly recommended. For belt-drive systems, the fans should be equipped with controls that periodically exercise them to keep the belts pliable and therefore more reliable.

Temperature in a battery area is crucial to the life expectancy and operation of the batteries. The optimum space temperature for lead-calcium batteries is 77°F. If higher temperatures are maintained, it may reduce battery life; if lower temperatures are maintained, it may reduce the batteries' ability to hold a charge (IEEE *Standard* 484).

Battery rooms should be maintained at a negative pressure to adjacent rooms and exhausted to the outside to prevent migration of fumes, gases, or electrolytic spray to other areas of the facility. It may be possible to provide makeup air from an adjacent datacom area, thereby eliminating the need for a separate HVAC system for the battery room, if temperatures are compatible. Battery rooms typically only have small heat-producing loads.

Battery rooms may require emergency eyewashes and showers. If so, these systems should include leak detection and remote alarm capabilities to alert staff of a possible leak or that an accident has occurred and emergency first aid is required.

Engine/Generator Rooms

Engine-driven generators used for primary or emergency power require large amounts of ventilation when running. This equipment is easier to start if a low ambient temperature is avoided. Low-temperature start problems are often reduced in cold climates by using engine block heaters. Design should ensure that exhaust air does not recirculate back to any building ventilation air intakes.

Spring-return motorized dampers are typically provided on air inlets and discharges and maintained normally closed when power is available to the damper actuator. Damper actuator signals are generally from the generator electrical gear as opposed to the building management system (BMS).

Where acoustical concerns exist, measures may need to be taken both inside the engine/generator room to meet the appropriate OSHA regulations and guidelines [e.g., OSHA (1996)] and on the air intake/discharge openings if the site is near an acoustically sensitive property line.

Burn-In Rooms and Test Labs

Many datacom facilities incorporate a dedicated area for the purpose of assembling, configuring and testing datacom equipment before deployment in the production environment. These areas can be used for testing equipment power supplies, dual-power capabilities, actual power draw, and cooling requirements, as well as for equipment applications testing (both software and hardware functions).

It is recommended that these areas be adjacent to production areas for convenience, yet separated with respect to power, cooling, and fire protection to prevent a power problem or fire from affecting the production environment.

Datacom Equipment Spare Parts

A spare parts room may require immediate use of parts for equipment repair. Therefore, the temperature of the space should be similar to that of the operating data center. ASHRAE's *Thermal Guidelines for Data Processing Environments* (ASHRAE 2004) provides allowable temperatures for "product power-off" conditions that include a spare parts room environment.

Storage Spaces

Storage spaces for products such as paper and tapes generally require conditions similar to those in data and communications equipment rooms, because these products absorb moisture from the air and can expand, contract, or change shape more than electronic equipment. Close-tolerance mechanical devices, such as paper feeders or tape drives, are also affected by room relative humidity.

OTHER SYSTEMS AND CONSIDERATIONS

Fire Suppression

Automatic fire extinguishing and smoke control systems afford the highest degree of protection and must be provided in accordance with the applicable national codes, local codes, and the owner's insurance underwriter. Some new code references require fire protection below the raised floor.

Exhaust Systems. Exhaust systems may be provided to ventilate datacom equipment rooms in the event of a chemical fire suppression system discharge or as required for smoke purge. Locating the exhaust pickup point below a supply plenum floor promotes quick purging of the space.

There is no need for a purge system when datacom equipment rooms are only protected with sprinklers unless required by code. Even so, the ability to purge datacom space (including critical infrastructure rooms) can minimize the effects of combustion contaminants on datacom equipment, regardless of the type of suppression system.

For small computer rooms that use DX compressor-based cooling systems, local codes may require alarm and exhaust in the event of loss of refrigerant. The volume of refrigerant within a system should be checked against local code requirements.

Fire Smoke Dampers. When motorized fire/smoke dampers are installed to seal a clean-agent-protected room, they must be the spring-loaded type, configured to close on loss of power (or upon melting of fusible link). During start-up, it is important to verify proper operation, including making sure that dampers close fully without binding. A binding damper jeopardizes the integrity of the room seal and could prevent the clean agent from reaching the proper concentration level to extinguish a fire. To increase reliability, mechanical systems should be designed to minimize the number of motorized fire/smoke dampers.

Outdoor Air Smoke Detectors. Outside air, and any other air supply, should be equipped with smoke detection that shuts down associated fans and closes associated fire/smoke damper(s). Roof fires, nearby fires, nearby chemical spills, and even generator start-up can introduce smoke and reactive chemicals into the data center through fresh air intakes.

Additional information on fire detection and suppression systems for datacom environments can be found in *Design Considerations for Datacom Equipment Centers* (ASHRAE 2005b).

Commissioning

Commissioning of datacom facilities is critical to their proper functioning and reliable operation. The commissioning process is usually misinterpreted as focusing on systems testing only, and initiated during the construction process.

However, ASHRAE *Guideline* 1 defines commissioning as "the process of ensuring that systems are designed, installed, functionally tested, and capable of being operated and maintained to perform in conformity with the design intent. . . . Commissioning begins with planning and includes design, construction, start-up, acceptance and training, and can be applied throughout the life of the building."

It is recommended that commissioning of datacom facilities begin at project inception, so that owner requirements can be better defined, addressed, and verified throughout the entire design and construction process. Five levels of commissioning are described in *Design Considerations for Datacom Equipment Centers* (ASHRAE 2005b):

- Level 1: factory acceptance tests
- Level 2: field component verification
- Level 3: system construction verification
- Level 4: site acceptance testing
- Level 5: integrated systems testing

Mission-critical facilities typically have more demanding performance requirements for responses to expected and unexpected anomalies without affecting critical operations. Systems usually include redundant components and utility feeds, and excess capacity or back up systems or equipment that, during an emergency, can be automatically or manually activated. These redundant or back-up components, systems, or groups of interrelated systems are tested during level 5 commissioning: this level is what generally sets mission-critical facility commissioning apart from typical office building commissioning.

Further information on commissioning can be found in Chapter 42 and ASHRAE *Guidelines* 0 and 1.

Serviceability

There are many serviceability issues to consider for HVAC equipment serving datacom facilities. Above all, the design should seek to coordinate with datacom facility operations to service and maintain equipment with the least amount of disruption to the day-to-day running of the facility. One approach is to locate all cooling equipment (e.g., CRAC or central station air-handling units) outside of the datacom equipment room in dedicated support rooms. Servicing and maintenance operations for this equipment is then performed in areas devoted specifically to air-conditioning equipment. System security for these spaces, however, must be addressed.

HVAC equipment serving datacom facilities can also be located on the roof, when the physical arrangement of the facility and space limitations allow.

Availability and Redundancy

It is extremely important to understand the need for uptime of the datacom facilities. Mission-critical datacom facilities, as their name implies, are often required to run 24 h, 7 days a week, all year round, and any disruption to that operation typically results in a loss of business continuity or revenue for the end user.

Availability is a percentage value representing the probability that a component or system will remain operational. Availability typically considers both component reliability and system maintenance (Beaty 2004). Values of 99.999% ("five 9s") and higher are commonly referenced in datacom facility design, but are difficult to attain. For individual components, availability is often determined through testing. For assemblies and systems, availability is often the result of a mathematical evaluation based on the availability of individual components and any redundancy or diversity that may be used.

Availability calculations for HVAC systems are seldom done and are extremely difficult, because published data on components and systems are not readily available. Further research is needed to allow for calculation of system availability as a function of component availability and level of redundancy.

System availability may be so vital that the potential cost of system failure justifies redundant systems, capacity, and/or components, as well as increased diversity. System simplicity and ease of operation should be a constant consideration; a substantial percentage of reported data center failures are related to human activity or error.

The most common method used to attain greater system availability is adding redundant parallel components to avoid a single component failure that causes a systemwide failure. HVAC system redundancy calculations commonly use the terms $N + 1$, $N + 2$, and $2N$ to indicate how many additional components are to be provided. N represents the number of pieces of equipment that it takes to satisfy the normal load. Redundant equipment is necessary to compensate for failures and allow maintenance to be performed without reducing the remaining online capacity below normal.

In the case of datacom facilities using CRAC units, if $N + 1$ redundancy is required, the number of units required to satisfy the

normal *N* cooling load must first be determined. One additional unit would then be provided, to achieve *N* + 1 redundancy.

In theory, redundancy can be achieved with *N* + 1 (or more air-handling or CRAC units), but the dynamics of underfloor and overhead flow are such that loss of a specific unit can be critical for a specific area. CFD analysis is often performed to determine the effect of losing specific units in critical-use areas. For large spaces, consider using *N* + 1 for every *X* number of units, to provide one redundant unit for every set of *X* units required.

Take care to exercise redundant equipment frequently, to prevent conditions that enhance growth of mold and mildew in filters, insulated unit enclosures, and outside air pathways where spores and food sources for microbial growth may accumulate. Another approach is to keep redundant equipment operational at all times, but to use variable-frequency drives (VFDs) to control fan speed. In this manner, the fans operate at a speed to match loads. If a fan fails, the other fans ramp up to maintain required airflows. No schedule is required for exercising equipment, because all equipment is operational (unless loads are so low that it is not practical to operate all equipment).

Diversity. Systems that use an alternative path for distribution are said to have diversity. In an HVAC system, diversity might be used to refer to an alternative chilled-water piping system. To be of maximum benefit, both the normal and alternative paths must each be able to support the entire normal load. One company developed a tiered classification system to rank the level of diversity and redundancy in a data center design (Turner and Brill 2003).

With dual feeds, it is often possible to perform planned datacom air-moving device infrastructure activity without shutting down critical loads, a concept called **concurrently maintainable**. **Fault-tolerant** systems do not lose power or cooling to the datacom equipment when a single component fails.

Measures to Increase Reliability. Practical ways to increase HVAC system reliability for datacom facility design may include any of the examples listed below. A fault tree analysis or other methodology should be used for each facility to examine critical failure paths and necessary design measures to increase system availability.

- Back-up utilities: power generation, second electric service, water supply, etc. Emergency power supplies probably should feed some aspects of HVAC systems as well as datacom equipment to allow for continuous equipment operation within allowable environmental conditions.
- Back-up air moving equipment: air handlers, fans, computer room units, etc.
- Back-up and/or cross-connected cooling equipment: chillers, pumps, cooling towers, dry coolers, cooling coils, makeup water supply, etc.
- Diverse piping systems: chilled water, condenser water, etc.
- Full or partial back-up of air-moving and/or cooling equipment on emergency power.
- Back-up thermal storage: chilled water, ice, makeup water, etc.

Energy Conservation

Dramatic reductions in energy use can be achieved with conservation strategies. Central-station air-conditioning systems using outside air for free cooling (where appropriate), variable-volume ventilation, and evaporative cooling/humidification strategies offer significant opportunities for reducing energy use, depending on the frequency of favorable outdoor conditions. A dew-point control strategy, often consisting of positive pressurization of the datacom facility and humidity control at the point of outdoor air intake, can eliminate the need for humidity-sensing devices and provide precise humidity control.

A significant amount of wasted energy has been identified in many existing facilities, often because of fighting between adjacent air-conditioning units attempting to maintain tight tolerances.

Adopting the somewhat less stringent environmental tolerances found in ASHRAE's (2004) *Thermal Guidelines for Data Processing Environments* should minimize this historically significant problem. Control strategies such as underfloor air temperature control and additional monitoring points should be considered to identify and avoid fighting, especially where raised-floor spaces may include a mixture of heat densities in the same open area.

Baseline energy consumption of office and telecommunications equipment was estimated by Roth (2002). Case studies of energy consumption in datacom facilities have been inventoried and are available for public review (LBNL 2003). Tschudi et al. (2003) summarized existing research on energy conservation in datacom facilities and provided a roadmap for further research in this area. Areas covered include monitoring and control, electrical systems, and HVAC systems (including free cooling), and use of variable-speed compressors in CRAC units. A set of recommendations for high-performance data centers has also recently been issued (RMI 2003).

Economizer Cycles. Air-side economizers are generally not used in datacom facilities for several reasons, including their potential effect on humidity levels and concern about dust contamination from the increased outdoor air. They are, however, required by energy conservation codes in some parts of the United States. ASHRAE's (2004) *Thermal Guidelines for Data Processing Environments* also allows increased economizer use in some climates, because of the higher recommended inlet air temperature range (68 to 77°F for Class 1 and 2 environments) relative to a typical office supply air temperature of 60°F or below.

Telecommunications central offices often use air-side economizers to save energy. When evaluating economizers, the potential reduction in cooling costs should be compared with the added costs derived from increased equipment soiling. Herrlin (1996) concluded that significant savings could be expected in most United States climates (except the Southeast) when enthalpy economizers are incorporated.

Fluid or glycol economizers are economically advantageous in many cold climates. Designs should be engineered to minimize cycling between free economizer cooling and mechanical cooling.

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CHAPTER 18

PRINTING PLANTS

THIS chapter outlines air-conditioning requirements for key printing operations. Air conditioning of printing plants can provide controlled, uniform air moisture content and temperature in working spaces. Paper, the principal material used in printing, is hygroscopic and very sensitive to variations in the humidity of the surrounding air. Printing problems caused by paper expansion and contraction can be avoided by controlling the moisture content throughout the manufacture and printing of the paper.

DESIGN CRITERIA

The following are three basic printing methods:

- **Relief printing (letterpress).** Ink is applied to a raised surface.
- **Lithography.** Inked surface is neither in relief nor recessed.
- **Gravure (intaglio printing).** Inked areas are recessed below the surface.

Figure 1 shows the general work flow through a printing plant. The operation begins at the publisher and ends with the finished printed product and paper waste. Paper waste, which may be as much as 20% of the total paper used, affects profitability. Proper air conditioning can help reduce the amount of paper wasted.

In sheetfed printing, individual sheets are fed through a press from a stack or load of sheets and collected after printing. In webfed rotary printing, a continuous web of paper is fed through the press

Fig. 1 Work Flow Through a Printing Plant

The preparation of this chapter is assigned to TC 9.2, Industrial Air Conditioning.

from a roll. The printed material is cut, folded, and delivered from the press as signatures, which form the sections of a book.

Sheetfed printing is a slow process in which the ink is essentially dry as the sheets are delivered from the press. **Offsetting**, the transference of an image from one sheet to another, is prevented by applying a powder or starch to separate each sheet as it is delivered from the press. Starches present a housekeeping problem: the particles (30 to 40 μm in size) tend to fly off, eventually settling on any horizontal surface.

If both temperature and relative humidity are maintained within normal human comfort limits, they have little to do with web breaks or the runnability of paper in a webfed press. At extremely low humidity, static electricity causes the paper to cling to the rollers, creating undue stress on the web, particularly with high-speed presses. Static electricity is also a hazard when flammable solvent inks are used.

Special Considerations

Various areas in printing plants require special attention to processing and heat loads.

Engraving and platemaking departments must have very clean air: not as clean as that for industrial cleanrooms, but cleaner than that for offices. Engraving and photographic areas may also have special ventilation needs because of the chemicals used. Nitric acid fumes from powderless etching require careful duct material selection. Composing rooms, which contain computer equipment, can be treated the same as similar office areas. The excessive dust from cutting in the stitching and binding operations must be controlled. Stereotype departments have very high heat loads.

In pressrooms, air distribution must not cause the web to flutter or force contaminants or heat (which normally would be removed by roof vents) down to the occupied level. Air should be introduced immediately above the occupied zone wherever possible to minimize total flow and encourage stratification. High air exchange rates may be required where solvent- or oil-based inks are used, because of the large quantity of organic solvent vapors that may be released from nonpoint sources. Exhaust emissions from dryer systems may contain substantial concentrations of solvent vapors, which must be captured and recovered or incinerated to satisfy local air pollution requirements. Where these measures are required, efforts should be made to maximize point-source capture of vapors to minimize the size, cost, and energy requirements for vapor recovery/incineration equipment. These efforts also minimize the effect of these requirements on general ventilation systems.

Conventional air-conditioning and air-handling equipment, particularly rooftop equipment, may be unable to handle the high outside air requirements of pressroom applications effectively. Stratified ventilation may be used in high-bay installations to reduce total system airflow and air-conditioning requirements. Pressrooms using oil- or solvent-based inks should be provided with a minimum of 0.5 cfm/ft^2 of outside air to ensure adequate dilution of internally
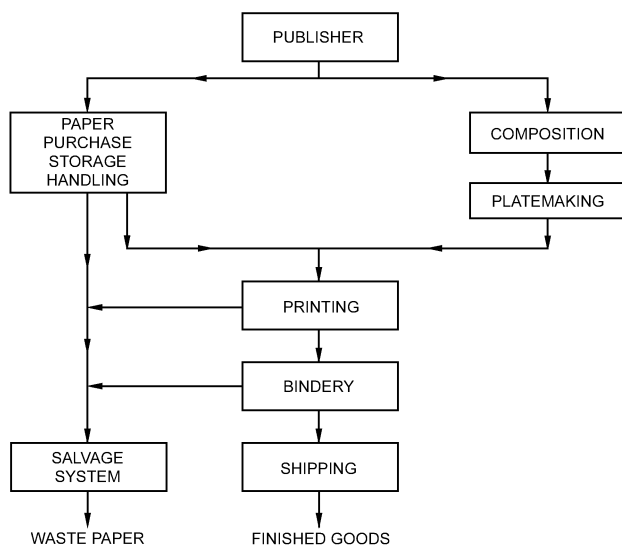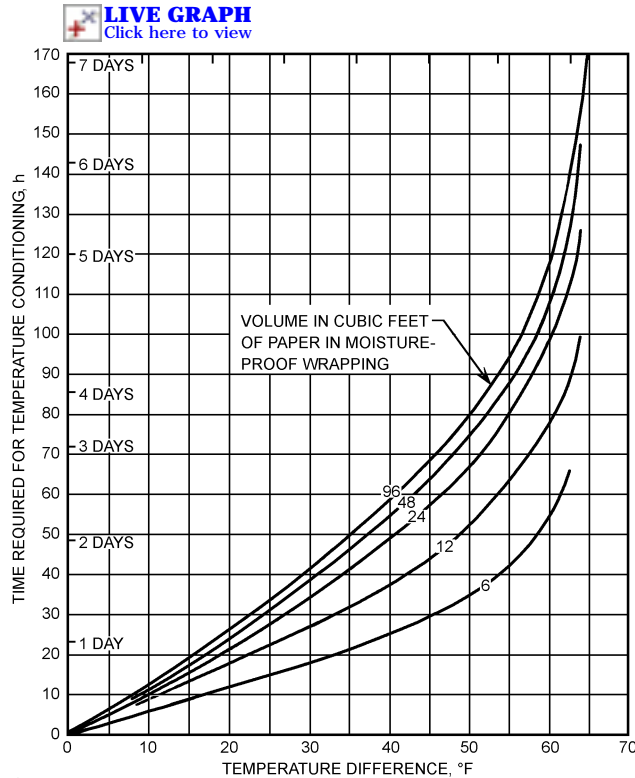
Fig. 2   Temperature-Conditioning Chart for Paper

generated volatile organic compounds. Ventilation of storage areas should be about 0.5 air changes per hour (ach); bindery ventilation should be about 1 ach. Storage areas with materials piled high may need roof-mounted smoke- and heat-venting devices.

In a bindery, loads of loose signatures are stacked near equipment, which makes it difficult to supply air to occupants without scattering the signatures. One solution is to run the main ducts at the ceiling with many supply branches dropped to within 8 to 10 ft of the floor. Conventional adjustable blow diffusers, often the linear type, are used.

CONTROL OF PAPER MOISTURE CONTENT

Controlling the moisture content and temperature of paper is important in all printing, particularly multicolor lithography. Paper should be received at the printing plant in moisture-proof wrappers, which are not broken or removed until the paper is brought to the pressroom temperature. When exposed to room temperature, paper at temperatures substantially below the room temperature rapidly absorbs moisture from the air, causing distortion. Figure 2 shows the time required to temperature-condition wrapped paper. Printers usually order paper with a moisture content approximately in equilibrium with the relative humidity maintained in their pressrooms. Papermakers find it difficult to supply paper in equilibrium with a relative humidity higher than 50%.

Digital hygrometers can be used to check the hygroscopic condition of paper relative to the surrounding air. The probes contain a moisture-sensitive element that measures the electrical conductivity of the paper. Intact mill wrappings and the tightness of the roll normally protect a paper roll for about six months. If the wrapper is damaged, moisture usually penetrates no more than 0.125 in.

PLATEMAKING

Humidity and temperature control are important considerations when making lithographic and collotype plates, photoengravings, and gravure plates and cylinders. If the moisture content and

temperature of the plates increase, the coatings increase in light sensitivity, which necessitates adjustments in the light intensity or the length of exposure to give uniformity.

If platemaking rooms are maintained at constant dry-bulb temperature and relative humidity, plates can be produced at known control conditions. As soon as it is dry, a bichromated colloid coating starts to age and harden at a rate that varies with the atmospheric conditions, so exposures made a few hours apart may be quite different. The rate of aging and hardening can be estimated more accurately when the space is air conditioned. Exposure can then be reduced progressively to maintain uniformity. An optimum relative humidity of 45% or less substantially increases the useful life of bichromated colloid coatings; the relative humidity control should be within 2%. A dry-bulb temperature of 75 to 80°F maintained within 2°F is good practice. The ventilation air requirements of the plate room should be investigated. A plant with a large production of deep-etch plates should consider locating this operation outside the conditioned area.

Exhausts for platemaking operations consist primarily of lateral or downdraft systems at each operation. Because of their bulkiness or weight, plates or cylinders are generally conveyed by overhead rail to the workstation, where they are lowered into the tank for plating, etching, or grinding. Exhaust ducts must be below or to one side of the working area, so lateral exhausts are generally used for open-surface tanks.

Exhaust quantities vary, depending on the nature of the solution and shape of the tank, but they should provide exhaust in accordance with the recommendations of *Industrial Ventilation* by the American Conference of Governmental Industrial Hygienists (ACGIH 2007) for a minimum control velocity of 50 fpm at the side of the tank opposite the exhaust intake. Tanks should be covered to minimize exhaust air quantities and increase efficiency. Excessive air turbulence above open tanks should be avoided. Because of the nature of the exhaust, ducts should be acid-resistant and liquidtight to prevent moisture condensation.

Webfed offset operations and related departments are similar to webfed letterpress operations, without the heat loads created in the composing room and stereotype departments. Special attention should be given to air cleanliness and ventilation in platemaking to avoid flaws in the plates caused by chemical fumes and dust.

A rotogravure plant can be hazardous because highly volatile solvents are used. Equipment must be explosionproof, and air-handling equipment must be sparkproof. Clean air must be supplied at controlled temperature and relative humidity.

Reclamation or destruction systems are used to prevent photosensitive hydrocarbons from being exhausted into the atmosphere. Some reclamation systems use activated carbon for continuous processing. Incineration or catalytic converters may be used to produce rapid oxidation to eliminate pollutants. The amount of solvents reclaimed may exceed that added to the ink.

RELIEF PRINTING

In relief printing (letterpress), rollers apply ink only to the raised surface of a printing plate. Pressure is then applied to transfer the ink from the raised surface directly to the paper. Only the raised surface touches the paper to transfer the desired image.

Air conditioning in newspaper pressrooms and other webfed letterpress printing areas minimizes problems caused by static electricity, ink mist, and expansion or contraction of the paper during printing. A wide range of operating conditions is satisfactory. The temperature should be selected for operator comfort.

At web speeds of 1000 to 2000 fpm, it is not necessary to control the relative humidity because inks are dried with heat. In some types of printing, moisture is applied to the web, and the web is passed over chill rolls to further set the ink.

Webfed letterpress ink is heat-set, made with high-boiling, slow-evaporating synthetic resins and petroleum oils dissolved or dispersed in a hydrocarbon solvent. The solvent must have a narrow boiling range with a low volatility at room temperatures and a fast evaporating rate at elevated temperatures. The solvent is vaporized in the printing press dryers at temperatures from 250 to 400°F, leaving the resins and oils on the paper. Webfed letterpress inks are dried after all colors are applied to the web.

The inks are dried by passing the web through dryers at speeds of 1000 to 2000 fpm. There are several types of dryers: open-flame gas cup, flame impingement, high-velocity hot air, and steam drum.

Exhaust quantities through a press dryer vary from about 7000 to 15,000 cfm at standard conditions, depending on the type of dryer used and the speed of the press. Exhaust temperatures range from 250 to 400°F.

Solvent-containing exhaust is heated to 1300°F in an air pollution control device to incinerate the effluent. A catalyst can be used to reduce the temperature required for combustion to 1000°F, but it requires periodic inspection and rejuvenation. Heat recovery reduces the fuel required for incineration and can be used to heat pressroom makeup air.

LITHOGRAPHY

Lithography uses a grease-treated printing image receptive to ink, on a surface that is neither raised nor depressed. Both grease and ink repel water. Water is applied to all areas of the plate, except the printing image. Ink is then applied only to the printing image and transferred to the paper in the printing process. In multicolor printing operations, the image may be printed up to four times on the same sheet of paper in different colors. Registration of images is critical to final color quality.

Offset printing transfers the image first to a rubber blanket and then to the paper. Sheetfed and web offset printing are similar to letterpress printing. The inks used are similar to those used in letterpress printing but contain water-resistant vehicles and pigment. In web offset and gravure printing, the relative humidity in the pressroom should be kept constant, and the temperature should be selected for comfort or, at least, to avoid heat stress. It is important to maintain steady conditions to ensure the dimensional stability of the paper onto which the images are printed.

The pressroom for sheet multicolor offset printing has more exacting humidity requirements than other printing processes. The paper must remain flat with constant dimensions during multicolor printing, in which the paper may make six or more passes through the press over a period of a week or more. If the paper does not have the right moisture content at the start, or if there are significant changes in atmospheric humidity during the process, the paper will not retain its dimensions and flatness, and misregistering will result. In many cases of color printing, a register accuracy of 0.005 in. is required. Figure 3 shows the close control of the air relative humidity that is necessary to achieve this register accuracy. The data shown in this figure are for composite lithographic paper.

Maintaining constant moisture content of the paper is complicated because paper picks up moisture from the moist offset blanket during printing (0.1 to 0.3% for each impression). When two or more printings are made in close register work, the paper at the start of the printing process should have a moisture content in equilibrium with air at 5 to 8% rh above the pressroom air. At this condition, the moisture evaporated from the paper into the air nearly balances the moisture added by the press. In obtaining register, it is important to keep the sheet flat and free from wavy or tight edges. To do this, the relative humidity balance of the paper should be slightly above that of the pressroom atmosphere. This balance is not as critical in four-color roll-feed presses because the press moisture does not penetrate the paper quickly enough between colors to affect sheet dimensions or cause sheet distortion.
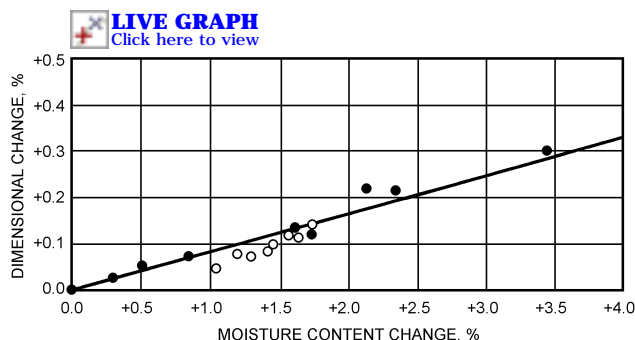
Fig. 3   Effects of Variation in Moisture Content on Dimensions of Printing Papers
(Weber and Snyder 1934)

Recommended Environment

The Graphic Arts Technical Foundation recommends ideal conditions in a lithographic pressroom of 76 to 80°F db and 43 to 47% rh, controlled to ±2°F db and ±2% rh (Reed 1970). Comfort and economy of operation influence the choice of temperature. The effect of relative humidity variations on register can be estimated for offset paper from Figure 3. Closer relative humidity control of the pressroom air is required for multicolor printing of 76 in. sheets than for 22 in. sheets with the same register accuracy. Closer control is needed for multicolor printing, where the sheet makes two or more trips through the press, than for one-color printing.

Ink drying is affected by temperature and humidity, so uniform results are difficult to obtain without controlling the atmospheric conditions. Printing inks must dry rapidly to prevent offsetting and smearing. High relative humidity and high moisture content in paper tend to prevent ink penetration, so more ink remains on the surface than can be quickly oxidized. This affects drying time, intensity of color, and uniformity of ink on the surface. Relative humidity below 60% is favorable for drying at a comfortable temperature. Higher relative humidity may cause severe paper distortion and significant damage to the final product.

The air conditioning for the pressroom of a lithographic plant should control air temperature and relative humidity, filter the air, supply ventilation air, and distribute the air without pronounced drafts around the presses. Using antioffset sprays to set the ink creates an additional air-filtering load from the pressroom. Drafts and high airflow over the presses lead to excessive drying of the ink and water, which causes scumming or other problems.

The operating procedures of the pressroom should be analyzed to determine the heat removal load. The lighting load is high and constant throughout the day. The temperature of the paper brought into the pressroom and the length of time it is in the room should be considered to determine the sensible load from the paper. Figure 2 shows the time required for wrapped paper to reach room temperature. The press motors usually generate a large portion of the internal sensible heat gain.

Readings should be taken to obtain the running power load of the larger multicolor presses. The moisture content of the paper fed to the press and the relative humidity of the air must be considered when computing the internal latent heat gain. Paper is used that is in equilibrium with air at a relative humidity somewhat higher than that of the pressroom, so the paper gives up moisture to the space as it absorbs moisture during printing. If the moisture transfer is in balance, water used in the printing process should be included in the internal moisture load. It is preferable to determine the water evaporation from the presses by testing.

Air Conditioning

Precise multicolor offset lithography printing requires either refrigeration with provision for separate humidity control, or sorption dehumidifying equipment for independent humidity

control with provision for cooling. The need for humidity control in the pressroom may be determined by calculating the dimensional change of the paper for each percent of change in relative humidity and checking this with the required register for the printing process.

Air conditioning of the photographic department is usually considered next in importance to that of the pressroom. Most of the work in offset lithography is done on film. Air conditioning controls cleanliness and comfort and maintains the size of the film for register work.

Air conditioning is important in the stripping department, both for comfort and for maintaining size and register. Curling of the film and flats, as well as shrinkage or stretch of materials, can be minimized by maintaining constant relative humidity. This is particularly important for close-register color work. The photographic area, stripping room, and platemaking area usually are maintained at the same conditions as the pressroom.

Dryers used for web offset printing are the same type as for webfed letterpress. Drying is not as complex because less ink is applied and presses run at lower speeds (800 to 1800 fpm).

ROTOGRAVURE

Rotogravure printing uses a cylinder with minute inkwells etched in the surface to form the printing image. Ink is applied to the cylinder, filling the wells. Excess ink is then removed from the cylinder surface by doctor blades, leaving only the ink in the wells. The image is then transferred to the paper as it passes between the printing cylinder and an impression cylinder.

In sheetfed gravure printing (as in offset printing), expansion, contraction, and distortion should be prevented to obtain correct register. The paper need not be in equilibrium with air at a relative humidity higher than that of the pressroom, because no moisture is added to the paper in the printing process. Humidity and temperature control should be exacting, like in offset printing. The relative humidity should be 45 to 50%, controlled to within ±2%, with a comfort temperature controlled to within ±2°F.

Gravure printing ink dries principally by evaporating the solvent in the ink, leaving a solid film of pigment and resin. The solvent is a low-boiling hydrocarbon, and evaporation takes place rapidly, even without the use of heat. The solvents have closed-cup flash points from 22 to 80°F and are classified as Group I or special hazard liquids by local code and insurance company standards. As a result, in areas adjacent to gravure press equipment and solvent and ink storage areas, electrical equipment must be Class I, Division 1 or 2, as described by the *National Electrical Code®* (NFPA *Standard* 70), and ventilation requirements (both supply and exhaust) are stringent. Ventilation should be designed for high reliability, with sensors to detect unsafe pollutant concentrations and then to initiate alarm or safety shutdown when necessary.

Rotogravure printing units operate in tandem, each superimposing print over that from the preceding unit. Press speeds range from 1200 to 2400 fpm. Each unit is equipped with its own dryer to prevent subsequent smearing or smudging.

A typical drying system consists of four dryers connected to an exhaust fan. Each dryer is equipped with fans to recirculate 5000 to 8000 cfm (at standard conditions) through a steam or hot water coil and then through jet nozzles. The hot air (130°F) impinges on the web and drives off the solvent-laden vapors from the ink. It is normal to exhaust half of this air. The system should be designed and adjusted to prevent solvent vapor concentration from exceeding 25% of its lower flammable limit (Marsailes 1970). If this is not possible, constant lower-flammable-limit (LFL) monitoring, concentration control, and safety shutdown capability should be included.

In exhaust design for a particular process, solvent vapor should be captured from the printing unit where paper enters and exits the dryer, from the fountain and sump area, and from the printed paper, which continues to release solvent vapor as it passes from one printing unit to another. Details of the process, such as ink and paper characteristics and rate of use, are required to determine exhaust quantities.

When dilution ventilation is used, exhaust of 1000 to 1500 cfm (at standard conditions) at the floor is often provided between each unit. The makeup air units are adjusted to supply slightly less air to the pressroom than that exhausted, to keep the pressroom negative with respect to the surrounding areas.

OTHER PLANT FUNCTIONS

Flexography

Flexography uses rubber raised printing plates and functions much like a letterpress. Flexography is used principally in the packaging industry to print labels and also to print on smooth surfaces, such as plastics and glass.

Collotype Printing

Collotype or photogelatin printing is a sheetfed printing process related to lithography. The printing surface is bichromated gelatin with varying affinity for ink and moisture, depending on the degree of light exposure received. There is no mechanical dampening as in lithography, and the necessary moisture in the gelatin printing surface is maintained by operating the press in an atmosphere of high relative humidity, usually about 85%. Because the tonal values printed are very sensitive to changes in the moisture content of the gelatin, the relative humidity should be maintained within ±2%.

Because tonal values are also very sensitive to changes in ink viscosity, temperature must be closely maintained; 80 ± 3°F is recommended. Collotype presses are usually partitioned off from the main plant, which is kept at a lower relative humidity, and the paper is exposed to high relative humidity only while it is being printed.

Salvage

Salvage systems remove paper trim and shredded paper waste from production areas, and carry airborne shavings to a cyclone or baghouse collector, where they are baled for recycling. Air quantities required are 40 to 45 ft^3 per pound of paper trim, and the transport velocity in the ductwork is 4500 to 5000 fpm (Marsailes 1970). Humidification may be provided to prevent the buildup of a static charge and consequent system blockage.

Air Filtration

Ventilation and air-conditioning systems for printing plants commonly use automatic moving-curtain dry-media filters with renewable media having a weight arrestance of 80 to 90% (ASHRAE *Standard* 52.1).

In sheetfed pressrooms, a high-performance final filter is used to filter starch particles, which require about 85% ASHRAE dust-spot efficiency. In film processing areas, which require relatively dust-free conditions, high-efficiency air filters are installed, with 90 to 95% ASHRAE dust-spot efficiency.

A different type of filtration problem in printing is **ink mist** or **ink fly**, which is common in newspaper pressrooms and in heatset letterpress or offset pressrooms. Minute droplets of ink (5 to 10 μm) are dispersed by ink rollers rotating in opposite directions. The cloud of ink droplets is electrostatically charged. Suppressors, charged to repel the ink back to the ink roller, are used to control ink mist. Additional control is provided by automatic moving curtain filters.

Binding and Shipping

Some printed materials must be bound. Two methods of binding are perfect binding and stitching. In **perfect binding**, sections of a book (signatures) are gathered, ruffed, glued, and trimmed. The

glued edge is flat. Large books are easily bound by this type of binding. Low-pressure compressed air and a vacuum are usually required to operate a perfect binder, and paper shavings are removed by a trimmer. The use of heated glue necessitates an exhaust system if the fumes are toxic.

In **stitching**, sections of a book are collected and stitched (stapled) together. Each signature is opened individually and laid over a moving chain. Careful handling of the paper is important. This has the same basic air requirements as perfect binding.

Mailing areas of a printing plant wrap, label, and ship the manufactured goods. Operation of the wrapper machine can be affected by low humidity. In winter, humidification of the bindery and mailing area to about 40 to 50% rh may be necessary to prevent static buildup.

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CHAPTER 19

TEXTILE PROCESSING PLANTS

THIS chapter covers (1) basic processes for making synthetic fibers, (2) fabricating synthetic fibers into yarn and fabric, (3) relevant types of HVAC and refrigerating equipment, (4) health considerations, and (5) energy conservation procedures.

Most textile manufacturing processes may be placed into one of three general classifications: synthetic fiber making, yarn making, or fabric making. Synthetic fiber manufacturing is divided into staple processing, tow-to-top conversion, and continuous fiber processing; yarn making is divided into spinning and twisting; and fabric making is divided into weaving and knitting. Although these processes vary, their descriptions reveal the principles on which air-conditioning design for these facilities is based.

TERMINOLOGY

The following is a only partial glossary of terms used in the textile industry. For more complete terminology, consult the sources in the Bibliography or the Internet search engine of your choice.

Air permeability. Porosity, or ease with which air passes through material. Air permeability affects factors such as the wind resistance of sailcloth, air resistance of parachute cloth, and efficiency of various types of air filtration media. It is also a measure of a fabric's warmness or coolness.

Bidirectional fabric. A fabric with reinforcing fibers in two directions: in the warp (machine) direction and filling (cross-machine) direction.

Calender. A machine used in finishing to impart various surface effects to fabrics. It essentially consists of two or more heavy rollers, sometimes heated, through which the fabric is passed under heavy pressure.

Denier. The weight, in grams, of 9000 m (29,528 ft) of yarn. Denier is a direct numbering system in which lower numbers represent finer sizes and higher numbers the coarser sizes. Outside the United States, the **Tex** system is used instead.

Heddle. A cord, round steel wire, or thin flat steel strip with a loop or eye near the center, through which one or more warp threads pass on the loom, so that thread movement may be controlled in weaving. Heddles are held at both ends by the harness frame. They control the weave pattern and shed as the harnesses are raised and lowered during weaving.

Lubricant. An oil or emulsion finish applied to fibers to prevent damage during textile processing, or to knitting yarns to make them more pliable.

Machine direction. The long direction within the plane of the fabric (i.e., the direction in which the fabric is being produced by the machine).

The preparation of this chapter is assigned to TC 9.2, Industrial Air Conditioning.

Pick. A single filling thread carried by one trip of the weft insertion device across the loom. Picks interface with the warp ends to form a woven fabric.

Reed. A comblike device on a loom that separates the warp yarns and also beats each succeeding filling thread against those already woven. The space between two adjacent wires of the reed is called a **dent**. The fineness of the reed is calculated by the number of dents per inch: the more dents, the finer the reed.

Selvage. The narrow edge of woven fabric that runs parallel to the warp. It is made with stronger yarns in a tighter construction than the body of the fabric, to prevent raveling. A **fast selvage** encloses all or part of the picks; a selvage is not fast when the filling threads are cut at the fabric edge after each pick.

Shuttle. A boat-shaped device usually made of wood with a metal tip that carries filling yarns through the shed in the weaving process.

Tex. The mass, in grams, of 1000 m (3281 ft) of fabric. Used primarily outside the United States. *See also* **Denier**.

Warp. The set of yarn in all woven fabrics, running lengthwise and parallel to the selvage, interwoven with the filling.

FIBER MAKING

Processes preceding fiber extrusion have diverse ventilating and air-conditioning requirements based on principles similar to those that apply to chemical plants.

Synthetic fibers are extruded from metallic spinnerets and solidified as continuous parallel filaments. This process, called **continuous spinning**, differs from the mechanical spinning of fibers or tow into yarn, which is generally referred to as **spinning**.

Synthetic fibers may be formed by melt-spinning, dry-spinning, or wet-spinning. Melt-spun fibers are solidified by cooling the molten polymer; dry-spun fibers by evaporating a solvent, leaving the polymer in fiber form; and wet-spun fibers by hardening the extruded filaments in a liquid bath. The selection of a spinning method is affected by economic and chemical considerations. Generally, nylons, polyesters, and glass fibers are melt-spun; acetates dry-spun; rayons and aramids wet-spun; and acrylics dry- or wet-spun.

For melt- and dry-spun fibers, the filaments of each spinneret are usually drawn through a long vertical tube called a **chimney** or **quench stack**, within which solidification occurs. For wet-spun fibers, the spinneret is suspended in a chemical bath where coagulation of the fibers takes place. Wet-spinning is followed by washing, applying a finish, and drying.

Synthetic continuous fibers are extruded as a heavy denier tow for cutting into short lengths called staple or somewhat longer lengths for tow-to-top conversion, or they are extruded as light denier filaments for processing as continuous fibers. An oil is then applied to lubricate, give antistatic properties, and control fiber cohesion. The extruded filaments are usually drawn (stretched) both to align the molecules along the axis of the fiber and to improve the

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crystalline structure of the molecules, thereby increasing the fiber's strength and resistance to stretching.

Heat applied to the fiber when drawing heavy denier or high-strength synthetics releases a troublesome oil mist. In addition, the mechanical work of drawing generates a high localized heat load. If the draw is accompanied by twist, it is called **draw-twist**; if not, it is called **draw-wind**. After draw-twisting, continuous fibers may be given additional twist or may be sent directly to warping.

When tow is cut to make staple, the short fibers are allowed to assume random orientation. The staple, alone or in a blend, is then usually processed as described in the Cotton System section. However, tow-to-top conversion, a more efficient process, has become more popular. The longer tow is broken or cut to maintain parallel orientation. Most of the steps of the cotton system are bypassed; the parallel fibers are ready for blending and mechanical spinning into yarn.

In the manufacture of glass fiber yarn, light denier multifilaments are formed by attenuating molten glass through platinum bushings at high temperatures and speeds. The filaments are then drawn together while being cooled with a water spray, and a chemical size is applied to protect the fiber. This is all accomplished in a single process prior to winding the fiber for further processing.

YARN MAKING

The fiber length determines whether spinning or twisting must be used. Spun yarns are produced by loosely gathering synthetic staple, natural fibers, or blends into rope-like form; drawing them out to increase fiber parallelism, if required; and then twisting. Twisted (continuous filament) yarns are made by twisting mile-long monofilaments or multifilaments. Ply yarns are made in a similar manner from spun or twisted yarns.

The principles of mechanical spinning are applied in three different systems: cotton, woolen, and worsted. The cotton system is used for all cotton, most synthetic staple, and many blends. Woolen and worsted systems are used to spin most wool yarns, some wool blends, and synthetic fibers such as acrylics.

Cotton System

The cotton system was originally developed for spinning cotton yarn, but now its basic machinery is used to spin all varieties of staple, including wool, polyester, and blends. Most of the steps from raw materials to fabrics, along with the ranges of frequently used humidities, are outlined in Figure 1.

Opening, Blending, and Picking. The compressed tufts are partly opened, most foreign matter and some short fibers are removed, and the mass is put in an organized form. Some blending is desired to average the irregularities between bales or to mix different kinds of fiber. Synthetic staple, which is cleaner and more uniform, usually requires less preparation. The product of the picker is pneumatically conveyed to the feed rolls of the card.

Carding. This process lengthens the lap into a thin web, which is gathered into a rope-like form called a **sliver**. Further opening and fiber separation follows, as well as partial removal of short fiber and trash. The sliver is laid in an ascending spiral in cans of various diameters.

For heavy, low-count (length per unit of mass) yarns of average or lower quality, the card sliver goes directly to drawing. For lighter, high-count yarns requiring fineness, smoothness, and strength, the card sliver must first be combed.

Lapping. In sliver lapping, several slivers are placed side by side and drafted. In ribbon lapping, the resulting ribbons are laid one on another and drafted again. The doubling and redoubling averages out sliver irregularities; drafting improves fiber parallelism. Some recent processes lap only once before combing.

Combing. After lapping, the fibers are combed with fine metal teeth to substantially remove all fibers below a predetermined length, to remove any remaining foreign matter, and to improve fiber arrangement. The combed lap is then attenuated by drawing rolls and again condensed into a single sliver.

Drawing. Drawing follows either carding or combing and improves uniformity and fiber parallelism by doubling and drafting several individual slivers into a single composite strand. Doubling averages the thick and thin portions; drafting further attenuates the mass and improves parallelism.

Roving. Roving continues the processes of drafting and paralleling until the strand is a size suitable for spinning. A slight twist is inserted, and the strand is wound on large bobbins used for the next roving step or for spinning.

Spinning. Mechanical spinning simultaneously applies draft and twist. The packages (any form into or on which one or more ends can be wound) of roving are creeled at the top of the frame. The unwinding strand passes progressively through gear-driven drafting rolls, a yarn guide, the C-shaped traveler, and then to the bobbin. The vertical traverse of the ring causes the yarn to be placed in predetermined layers.

The difference in peripheral speed between the back and front rolls determines the draft. Twist is determined by the rate of front roll feed, spindle speed, and drag, which is related to the traveler weight.

The space between the nip or bite of the rolls is adjustable and must be slightly greater than the longest fiber. The speeds of front and back rolls are independently adjustable. Cotton spindles normally run at 8000 to 9000 rpm but may exceed 14,000 rpm. In ring
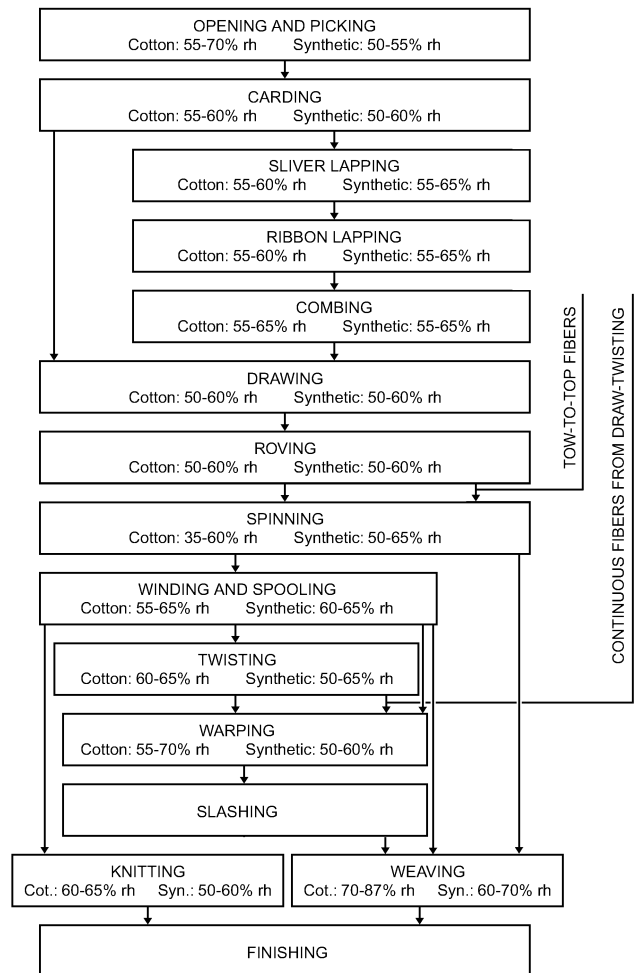
Fig. 1   Textile Process Flowchart and Ranges of Humidity

twisting, drawing rolls are omitted, and a few spindles run as high as 18,000 rpm.

Open-end or turbine spinning combines drawing, roving, lapping, and spinning. Staple fibers are fragmented as they are drawn from a sliver and fed into a small, fast-spinning centrifugal device. In this device, the fibers are oriented and discharged as yarn; twist is imparted by the rotating turbine. This system is faster, quieter, and less dusty than ring spinning.

Spinning is the final step in the cotton system; the feature that distinguishes it from twisting is the application of draft. The amount and point of draft application accounts for many of the subtle differences that require different humidities for apparently identical processes.

Atmospheric Conditions. From carding to roving, the loosely bound fibers are vulnerable to static electricity. In most instances, static can be adequately suppressed with humidity, which should not be so high as to cause other problems. In other instances, it is necessary to suppress electrostatic properties with antistatic agents. Wherever draft is applied, constant humidity is needed to maintain optimum frictional uniformity between adjacent fibers and, hence, cross-sectional uniformity.

Woolen and Worsted Systems

The woolen system generally makes coarser yarns, whereas the worsted system makes finer ones of a somewhat harder twist. Both may be used for lighter blends of wool, as well as for synthetic fibers with the characteristics of wool. The machinery used in both systems applies the same principles of draft and twist but differs greatly in detail and is more complex than that used for cotton.

Compared to cotton, wool fibers are dirtier, greasier, and more irregular. They are scoured to remove grease and are then usually reimpregnated with controlled amounts of oil to make them less hydrophilic and to provide better interfiber behavior. Wool fibers are scaly and curly, so they are more cohesive and require different treatment. Wool, in contrast to cotton and synthetic fibers, requires higher humidities in the processes prior to and including spinning than it does in the processes that follow. Approximate humidities are given in Kirk and Othmer (1993).

Twisting Filaments and Yarns

Twisting was originally applied to silk filaments; several filaments were doubled and then twisted to improve strength, uniformity, and elasticity. Essentially the same process is used today, but it is now extended to spun yarns, as well as to single or multiple filaments of synthetic fibers. Twisting is widely used in the manufacture of sewing thread, twine, tire cord, tufting yarn, rug yarn, ply yarn, and some knitting yarns.

Twisting and doubling is done on a **down-** or **ring-twister**, which draws in two or more ends from packages on an elevated creel, twists them together, and winds them into a package. Except for the omission of drafting, down-twisters are similar to conventional ring-spinning frames.

When yarns are to be twisted without doubling, an **up-twister** is used. Up-twisters are primarily used for throwing synthetic monofilaments and multifilaments to add to or vary elasticity, light reflection, and abrasion resistance. As with spinning, yarn characteristics are controlled by making the twist hard or soft, right (S) or left (Z). Quality is determined largely by the uniformity of twist, which, in turn, depends primarily on the tension and stability of the atmospheric conditions (Figure 1). Because the frame may be double- or triple-decked, twisting requires concentrations of power. The frames are otherwise similar to those used in spinning, and they present the same air distribution problems. In twisting, lint is not a serious problem.

FABRIC MAKING

Preparatory Processes

When spinning or twisting is complete, the yarn may be prepared for weaving or knitting by processes that include winding, spooling, creeling, beaming, slashing, sizing, and dyeing. These processes have two purposes: (1) to transfer the yarn from the type of package dictated by the preceding process to a type suitable for the next and (2) to impregnate some of the yarn with sizes, gums, or other chemicals that may not be left in the final product.

Filling Yarn. Filling yarn is wound on quills for use in a loom shuttle. It is sometimes predyed and must be put into a form suitable for package or skein dyeing before it is quilled. If the filling is of relatively hard twist, it may be put through a twist-setting or conditioning operation in which internal stresses are relieved by applying heat, moisture, or both.

Warp Yarn. Warp yarn is impregnated with a transient coating of size or starch that strengthens the yarn's resistance to the chafing it will receive in the loom. The yarn is first rewound onto a cone or other large package from which it will unwind speedily and smoothly. The second step is warping, which rewinds a multiplicity of ends in parallel arrangement on large spools, called **warp or section beams**. In the third step, slashing, the threads pass progressively through the sizing solution, through squeeze rolls, and then around cans, around steam-heated drying cylinders, or through an air-drying chamber. As much as several thousand pounds may be wound on a single loom beam.

Knitting Yarn. If hard-spun, knitting yarn must be twist-set to minimize kinking. Filament yarns must be sized to reduce strip-backs and improve other running qualities. Both must be put in the form of cones or other suitable packages.

Uniform tension is of great importance in maintaining uniform package density. Yarns tend to hang up when unwound from a hard package or slough off from a soft one, and both tendencies are aggravated by spottiness. The processes that require air conditioning, along with recommended relative humidities, are presented in Figure 1.

Weaving

In the simplest form of weaving, harnesses raise or depress alternate warp threads to form an opening called a **shed**. A shuttle containing a quill is kicked through the opening, trailing a thread of filling behind it. The lay and the reed then beat the thread firmly into one apex of the shed and up to the fell of the previously woven cloth. Each shuttle passage forms a pick. These actions are repeated at frequencies up to five per second.

Each warp thread usually passes through a drop-wire that is released by a thread break and automatically stops the loom. Another automatic mechanism inserts a new quill in the shuttle as the previous one is emptied, without stopping the loom. Other mechanisms are actuated by filling breaks, improper shuttle boxing, and the like, which stop the loom until it is manually restarted. Each cycle may leave a stop mark sufficient to cause an imperfection that may not be apparent until the fabric is dyed.

Beyond this basic machine and pattern are many complex variations in harness and shuttle control, which result in intricate and novel weaving effects. The most complex loom is the **jacquard**, with which individual warp threads may be separately controlled. Other variations appear in looms for such products as narrow fabrics, carpets, and pile fabrics. In the **Sulzer weaving machine**, a special filling carrier replaces the conventional shuttle. In the rapier, a flat, spring-like tape uncoils from each side and meets in the middle to transfer the grasp on the filling. In the **water jet loom**, a tiny jet of high-pressure water carries the filling through the shed of the warp. Other looms transport the filling with compressed air.

High humidity increases the abrasion resistance of the warp. Weave rooms require 80 to 85% humidity or higher for cotton and

up to 70% humidity for synthetic fibers. Many looms run faster when room humidity and temperature are precisely controlled.

In the weave room, power distribution is uniform, with an average concentration somewhat lower than in spinning. The rough treatment of fibers liberates many minute particles of both fiber and size, thereby creating considerable amounts of airborne dust. In this high-humidity area, air changes average from four to eight per hour. Special provisions must be made for maintaining conditions during production shutdown periods, usually at a lower relative humidity.

Knitting

Typical knitted products are seamless articles produced on circular machines (e.g., undershirts, socks, and hosiery) and those knitted flat (e.g., full-fashioned hosiery, tricot, milanese, and warp fabrics).

Knitted fabric is generated by forming millions of interlocking loops. In its simplest form, a single end is fed to needles that are actuated in sequence. In more complex constructions, hundreds of ends may be fed to groups of elements that function more or less in parallel.

Knitting yarns may be either single strand or multifilament and must be of uniform high quality and free from neps or knots. These yarns, particularly the multifilament type, are usually treated with special sizes to provide lubrication and to keep broken filaments from stripping back.

The need for precise control of yarn tension, through controlled temperature and relative humidity, increases with the fineness of the product. For example, in finer gages of full-fashioned hosiery, a 2°F change in temperature is the limit, and a 10% change in humidity may change the length of a stocking by 3 in. For knitting, desirable room conditions are approximately 76°F db and 45 to 65% rh.

Dyeing and Finishing

Finishing, which is the final readying of a mill product for its particular market, ranges from cleaning to imparting special characteristics. The specific operations involved vary considerably, depending on the type of fiber, yarn, or fabric, and the end product usage. Operations are usually done in separate plants. These areas need not only normal heating, ventilation, and fog removal systems, but also removal of hot, dusty, and toxic fumes from continuous ovens and tenters. Packaged chilling equipment is sometimes used to control temperatures of preshrink chemicals, dyes, and coatings that are applied to textiles and yarns before finishing. Some of these processes require corrosive-resistant materials and equipment.

Inspection is the only finishing operation to which air conditioning is regularly applied, although most of the others require ventilation. Finishing operations that use wet processes usually keep their solutions at high temperatures and require special ventilation to prevent destructive condensation and fog. Spot cooling of workers may be necessary for large releases of sensible, latent, or radiant heat.

AIR-CONDITIONING DESIGN

There are many diverse and special needs of specific areas of the textile process. Generally, a meeting with the owner's representative(s), local code officials, and the owner's insurance company is helpful in satisfying the particular requirements of the process, insurance companies, and local officials. HVAC engineers designing textile projects need to have a thorough understanding of the following HVAC system elements:

- Psychrometric process in spray systems
- Humidification and dehumidification
- Draft-free air distribution
- Fog control
- Water and air filters
- Dust collectors
- Industrial ductwork
- Large built-up air handlers

- Large water chillers
- Cooling towers
- Industrial piping systems
- Pumping
- Corrosion-resistant metallurgy
- Large centrifugal air compressors
- Programmable logic controllers and supervisory control and data acquisition (SCADA) systems
- Water treatment in open sump systems

Consultation with mechanical contracting companies experienced with building and installing textile-related systems provides great insight to these attributes. Thorough understanding of the processes to be conditioned; precise calculations; familiarity with codes, regulations, and current industry standards; as well as reasonable owner/engineer/contractor relationships and adherence to the owner's budget are necessary for successful projects.

Air washers are especially important in textile manufacturing and may be either conventional low-velocity or high-velocity units in built-up systems. Unitary high-velocity equipment using rotating eliminators, although no longer common, is still found in some plants.

Contamination of air washers by airborne oils often dictates the separation of air washers and process chillers by heat exchangers, usually of the plate or frame type.

Open Sump Chilled Water Systems

It is common practice to use open sumps in textile processing with air washer air-handling units. Open sumps present a unique problem for the removal of lint from the basins. Many systems return the air from spinning areas, and this air carries lint and free fibers from the spinning process. These fibers are typically not completely removed by central collectors (see Figure 3). In older facilities, the central collectors may be totally ineffective or nonexistent. A rotating drum filter is commonly used to remove lint fibers from the sumps of air washers to prevent clogging of spray nozzles and fouling of spray media. The rotating drum filters are semisubmerged in the sump and are fitted with a vacuum system that traverses the part of the drum that is exposed to air, removing the lint from the drum surface and transporting it through a high-pressure blower to a bag house, where water is separated and the lint collected for future disposal.

Many textile plants have an open sump for return of chilled water from the air washers (see A in Figure 2). The chilled water pumps draw out of these sumps through a screened inlet, C, for return of chilled water to the chillers. In designing the inlet screen, care must be taken to avoid a configuration that might lead to pump cavitation. Rotating drum filters should also be considered for these sumps to prevent fouling of chiller tubes by lint that passes the screens. These sumps must be carefully sized to receive the volume of water contained in the system when the air washers are shut off and their sumps drain down.

Integrated Systems

Many mills use a refined air washer system that combines the air-conditioning system and the collector system (see the section on Collector Systems) into an integrated unit. Air handled by the collector system fans and any air required to make up total return air are delivered back to the air-conditioning apparatus through a central duct. The quantity of air returned by individual yarn-processing machine cleaning systems must not exceed the air-conditioning supply air quantity. Air discharged by these individual suction systems is carried by return air ducts directly to the air-conditioning system. Before entering the duct, some of the cleaning system air passes over the yarn-processing machine drive motor and through a special enclosure to capture heat losses from the motor.
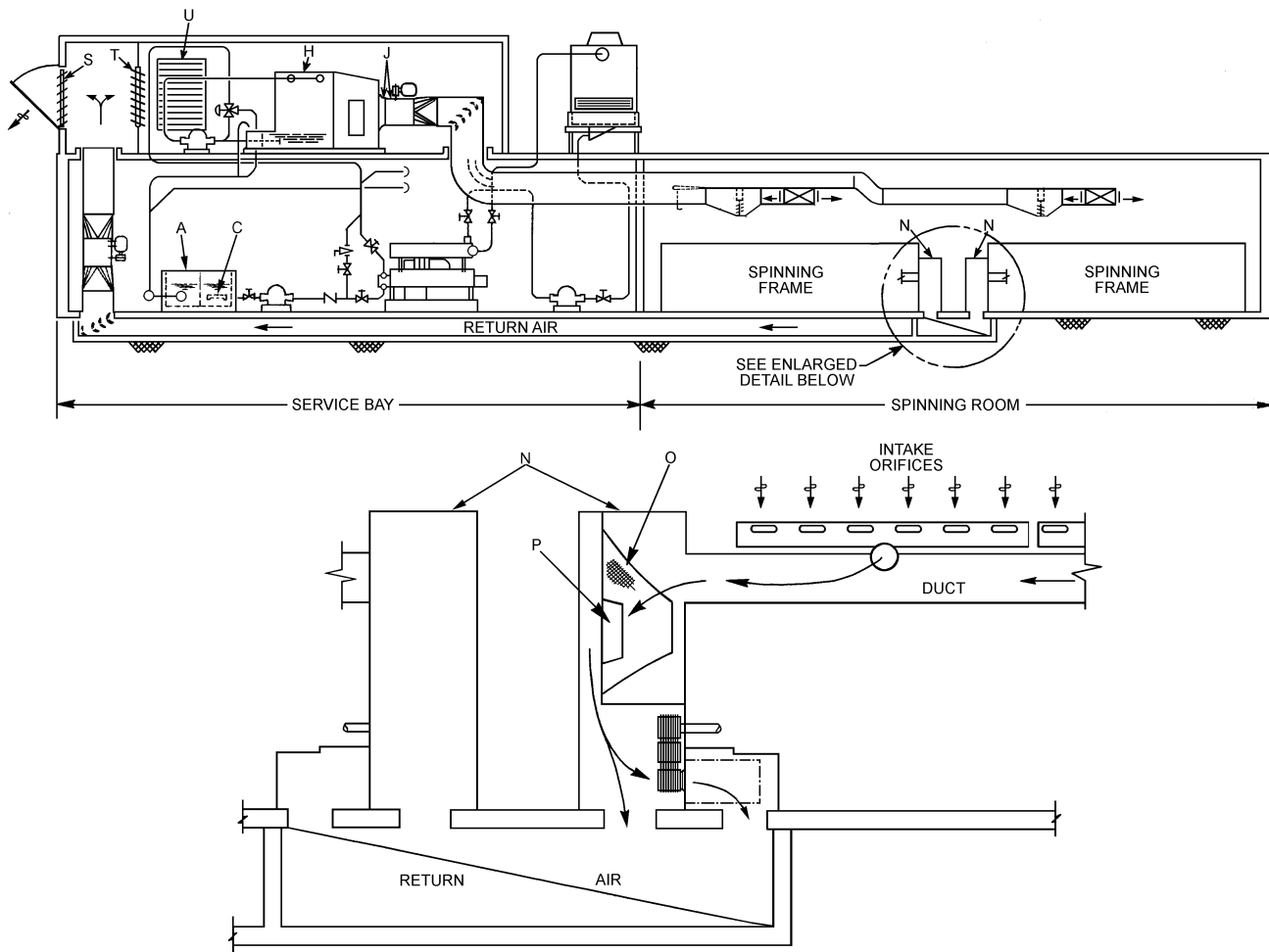
Fig. 2   Mechanical Spinning Room with Combined Air-Conditioning and Collector System

When integrated systems occasionally exceed the supply air requirements of the area served, the surplus air must be reintroduced after filtering.

Individual suction cleaning systems that can be integrated with air conditioning are available for cards, drawing frames, lap winders, combers, roving frames, spinning frames, spoolers, and warpers. The following advantages result from this integration:

- With a constant air supply, the best uniform air distribution can be maintained year-round.

- Downward airflow can be controlled; crosscurrents in the room are minimized or eliminated; drift or fly from one process to another is minimized or eliminated. Room partitioning between systems serving different types of manufacturing processes further enhances the value of this integration by controlling room air pattern year-round.

- Heat losses of the yarn-processing frame motor and any portion of the processing frame heat captured in the duct, as well as the heat of the collector system equipment, cannot affect room conditions; hot spots in motor alleys are eliminated, and although this heat goes into the refrigeration load, it does not enter the room. As a result, the supply air quantity can be reduced.

- Uniform conditions in the room improve production; conditioned air is drawn directly to the work areas on the machines, minimizing or eliminating wet or dry spots.

- Maximum cleaning use is made of the air being moved. A guide for cleaning air requirements follows:

Pickers	2500 to 4000 cfm per picker
Cards	700 to 1500 cfm per card
Spinning	4 to 8 cfm per spindle
Spooling	40 cfm per spool

Collector Systems

A collector system is a waste-capturing device that uses many orifices operating at high suction pressures. Each piece of production machinery is equipped with suction orifices at all points of major lint generation. The captured waste is generally collected in a fan and filter unit located either on each machine or centrally to accept waste from a group of machines.

A collector in the production area may discharge waste-filtered air either back into the production area or into a return duct to the air-conditioning system. It then enters the air washer or is relieved through dampers to the outdoors.

Figure 2 shows a mechanical spinning room with air-conditioning and collector systems combined into an integrated unit. In this case, the collector system returns all of its air to the air-conditioning system. If supply air from the air-conditioning system exceeds the maximum that can be handled by the collector system, additional air should be returned by other means.

Figure 2 also shows return air entering the air-conditioning system through damper T, passing through air washer H, and being
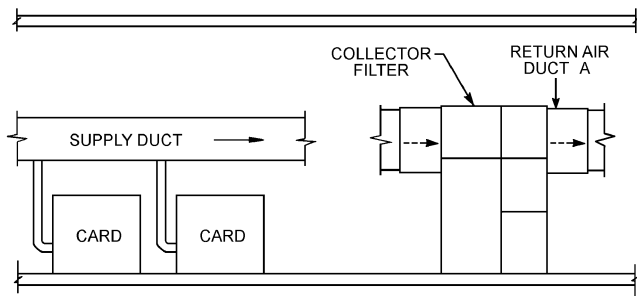
Fig. 3   Central Collector for Carding Machine

delivered by fan J to the supply duct, which distributes it to maintain conditions within the spinning room. At the other end of each spinning frame are unitary filter-collectors consisting of enclosure N, collector unit screen O, and collector unit fan P.

Collector fan P draws air through the intake orifices spaced along the spinning frame. This air passes through the duct that runs lengthwise to the spinning frame, passes through screen O, and is then discharged into the enclosure base (beneath the fan and screen). The air quantity is not constant; it drops slightly as material builds up on the filter screen.

Because the return air quantity must remain constant, and the air quantity discharged by fan P is slightly reduced at times, relief openings are necessary. Relief openings also may be required when the return air volume is greater than the amount of air the collector suction system can handle.

The discharge of fan P is split, so part of the air cools the spinning frame drive motor before rejoining the rest of the air in the return air tunnel. Regardless of whether the total return air quantity enters the return air tunnel through collector units, or through a combination of collector units and floor openings beneath spinning frames, return air fan R delivers it into the apparatus, ahead of return air damper T. Consideration should be given to filtering the return air prior to its delivery into the air-conditioning apparatus.

Mild-season operation causes more outdoor air to be introduced through damper U. This air is relieved through motorized damper S, which opens gradually as outdoor damper U opens, while return damper T closes in proportion. All other components perform as typical central station air-washer systems.

A system having the general configuration shown in Figure 2 may also be used for carding; the collector system portion of this arrangement is shown in Figure 3. A central collector filters the lint-laden air taken from multiple points on each card. This air is discharged to return air duct A and is then either returned to the air-conditioning system, exhausted outside, or returned directly to the room. A central collector filter may also be used with the spinning room system of Figure 2.

Air Distribution

Textile plants served by generally uniform air distribution may still require special handling for areas of load concentration.

Continuous Spinning Area. Methods of distribution are diverse and generally not critical. However, spot cooling or localized heat removal may be required. This area may be cooled by air conditioning, evaporative cooling, or ventilation.

Chimney (Quench Stack). Carefully controlled and filtered air or other gas is delivered to the chimneys; it is returned for conditioning and recovery of any valuable solvents present. Distribution of the air is of the utmost importance. Nonuniform temperature, humidity, or airflow disturbs the yarn, causing variations in fiber diameter, crystalline structure, and orientation. A fabric made of such fibers streaks when dyed.

In melt spinning, the solvent concentration in the chimney air must be maintained below its explosive limit. Care is still required to prevent vapors from being ignited by a spark or flame. The air-conditioning system must be reliable, because interruption of the spinning causes the solution to solidify in the spinnerets.

Wind-Up or Take-Up Areas of Continuous Spinning. A heavy air-conditioning load is developed. Air is often delivered through branch ducts alongside each spinning machine. Low-velocity, low-aspiration diffusers must be sized not to agitate delicate fibers.

Draw-Twist or Draw-Wind Areas of Fiber Manufacture. A heavy air-conditioning load is developed. Distribution, diffusion, and return systems are similar to those for the continuous spinning take-up area.

Opening and Picking. Usually, opening and picking require only a uniform distribution system. The area is subject to shutdown of machinery during portions of the day. Generally, an all-air system with independent zoning is installed.

Carding. A uniform distribution system is generally installed. There should be little air movement around the web in cotton carding. Central lint collecting systems are available but must be incorporated into the system design. An all-air system is often selected for cotton carding.

In wool carding, there should be less air movement than in cotton carding, not only to avoid disturbing the web, but also to reduce cross-contamination between adjacent cards. This is because different colors of predyed wool may be run side by side on adjacent cards. A split system (i.e., separate systems for each card) may be considered for wool carding to reduce air movement. The method of returning air is also critical for achieving uniform conditions.

Drawing and Roving. Generally, a uniform distribution all-air system works well.

Mechanical Spinning Areas. A heavy air-conditioning load is generated, consisting of spinning frame power uniformly distributed along the frame length and frame driver motor losses concentrated in the motor alley at one end of the frame.

Supply air ducts should run across the frames at right angles. Sidewall outlets between each of the two adjacent frames then direct the supply air down between the frames, where conditions must be maintained. Where concentrated heat loads occur, as in a double motor alley, placement of a supply air duct directly over the alley should be considered. Sidewall outlets spaced along the bottom of the duct diffuse air into the motor alley.

The collecting system, whether unitary or central, with intake points distributed along the frame length at the working level, assists in pulling supply air down to the frame, where maintenance of conditions is most important. A small percentage of the air handled by a central collecting system may be used to convey the collected lint and yarn to a central point, thus removing that air from the spinning room.

Machine design in spinning systems sometimes requires interfloor air pressure control.

Winding and Spooling. Generally, a uniform distribution, all-air system is used.

Twisting. This area has a heavy air-conditioning load. Distribution considerations are similar to those in spinning. Either all-air or split systems are installed.

Warping. This area has a very light load. Long lengths of yarn may be exposed unsupported in this area. Generally, an all-air system with uniform distribution is installed. Diffusers may be of the low-aspiration type. Return air is often near the floor.

Weaving. Generally, a uniform distribution system is necessary. Synthetic fibers are more commonly woven than natural fibers. The lower humidity requirements of synthetic fibers allow the use of an all-air system rather than the previously common split system. When lower humidity is coupled with the water jet loom, a high latent load results.

Health Considerations

For detailed information on control of industrial contaminants, see Chapter 25 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*.

Control of Oil Mist. When textiles coated with lubricating oils are heated above 200°F in drawing operations in ovens, heated rolls, tenterframes, or dryers, an oil mist is liberated. If the oil mist is not collected at the source of emission and disposed of, a slightly odorous haze results.

Various devices have been proposed to separate oil mist from the exhaust air, such as fume incinerators, electrostatic precipitators, high-energy scrubbers, absorption devices, high-velocity filters, and condensers.

Spinning operations that generate oil mist must be provided with a high percentage (30 to 75%) of outside air. In high-speed spinning, 100% outside air is commonly used.

Operations such as drum cooling and air texturizing, which could contaminate the air with oil, require local exhausts.

Control of Monomer Fumes. Separate exhaust systems for monomers are required, with either wet- or dry-type collectors, depending on the fiber being spun. For example, caprolactam nylon spinning requires wet exhaust scrubbers.

Control of Hazardous Solvents. Provisions must be made for the containment, capture, and disposal of hazardous solvents.

Control of Cotton Dust. Byssinosis, also known as brown or white lung disease, is believed to be caused by a histamine-releasing substance in cotton, flax, and hemp dust. In the early stages of the disease, a cotton worker returning to work after a weekend experiences difficulty in breathing that is not relieved until later in the week. After 10 to 20 years, the breathing difficulty becomes continuous; even leaving the mill does not provide relief.

The U.S. Department of Labor enforces an OSHA standard of lint-free dust. The most promising means of control are improved exhaust procedures and filtration of recirculated air. Lint particles are 1 to 15 μm in diameter, so filtration equipment must be effective in this size range. Improvements in carding and picking that leave less trash in the raw cotton also help control lint.

Noise Control. The noise generated by HVAC equipment can be significant, especially if the textile equipment is modified to meet present safety criteria. For procedures to analyze and correct the noise from ventilating equipment, see Chapter 46.

Safety and Fire Protection

Oil mist can accumulate in ductwork and create a fire hazard. Periodic cleaning reduces the hazard, but provisions should be made to contain a fire with suppression devices such as fire-activated dampers and interior duct sprinklers.

ENERGY CONSERVATION

The following are some steps that can be taken to reduce energy consumption:

- Applying heat recovery to water and air
- Automating high-pressure dryers to save heat and compressed air
- Decreasing hot-water temperatures and increasing chilled-water temperatures for rinsing and washing in dyeing operations
- Replacing running washes with recirculating washes where practical
- Changing double-bleaching procedures to single-bleaching where practical
- Eliminating rinses and final wash in dye operations where practical
- Drying by "bump and run" process
- Modifying drying or curing oven air-circulation systems to provide counterflow
- Using energy-efficient electric motors and textile machinery
- For drying operations, using discharge air humidity measurements to control the exhaust versus recirculation rates in full economizer cycles

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CHAPTER 20

PHOTOGRAPHIC MATERIAL FACILITIES

PROCESSING and storing sensitized photographic products requires temperature, humidity, and air quality control. Manufacturers of photographic products and processing equipment provide specific recommendations for facility design and equipment installation that should always be consulted. This chapter contains general information that can be used in conjunction with these recommendations. See Chapter 29 for information on general industrial ventilation.

STORING UNPROCESSED PHOTOGRAPHIC MATERIALS

Virtually all photosensitive materials deteriorate with age; the rate of photosensitivity deterioration depends largely on the storage conditions. Photosensitivity deterioration increases both at high temperature and at high relative humidity and usually decreases at lower temperature and humidity.

High humidity can accelerate loss of sensitivity and contrast, increase shrinkage, produce mottle (spots or blotches of different shades or colors), cause softening of the emulsion (which can lead to scratches), and promote fungal growth. Low relative humidity can increase the susceptibility of the film or paper to static markings, abrasions, brittleness, and curl.

Because different photographic products require different handling, product manufacturers should be consulted regarding proper temperature and humidity conditions for storage. Refrigerated storage may be necessary for some products in some climates.

Products not packaged in sealed vaportight containers are vulnerable to contaminants. These products must be protected from solvent, cleanser, and formaldehyde vapors (emitted by particleboard and some insulation, plastics, and glues); industrial gases; and engine exhaust. In hospitals, industrial plants, and laboratories, all photosensitive products, regardless of their packaging, must be protected from x-rays, radium, and radioactive sources. For example, films stored 25 ft away from 100 mg of radium require the protection of 3.5 in. of lead.

PROCESSING AND PRINTING PHOTOGRAPHIC MATERIALS

Ventilation with clean, fresh air maintains a comfortable working environment and prevents vapor-related complaints and health problems. It is also necessary for high-quality processing, safe handling, and safe storage of photographic materials.

Processing produces odors, vapors, high humidity, and heat (from lamps, electric motors, dryers, mounting presses, and high-temperature processing solutions). Thus, it is important to supply plentiful clean, fresh air at the optimum temperature and relative humidity to all processing rooms. ASHRAE *Standard* 62.1 specifies 1.0 cfm/ft^2 of exhaust for darkrooms in Table 6-4.

Air Conditioning for Preparatory Operations

During receiving operations, exposed film is removed from its protective packaging for presplicing and processing. **Presplicing**

The preparation of this chapter is assigned to TC 9.2, Industrial Air Conditioning.

combines many individual rolls of film into a long roll to be processed. At high relative humidity, photographic emulsions become soft and can be scratched. At excessively low relative humidity, the film base is prone to static, sparking, and curl deformation. The presplice work area should be maintained at 50 to 55% rh and 70 to 75°F db. Room pressures should cascade downward from areas of higher air quality to areas of lower air quality (clean to dirty).

Air Conditioning for Processing Operations

Processing exposed films or paper involves using a series of tempered chemical and wash tanks that emit heat, humidity, and vapors or gases (e.g., water vapor, acetic acid, benzyl alcohol, ammonia, sulfur dioxide). Room exhaust must be provided, along with local exhaust at noxious tanks. To conserve energy, air from pressurized presplice rooms can be used as makeup for processing room exhaust. Further supply air should maintain the processing space at a maximum of 75°F dry bulb and 50 to 55% rh.

The processed film or paper proceeds from the final wash to the dryer, which controls the moisture remaining in the product. Too little drying causes film to stick when wound, whereas too much drying causes undesirable curl. Drying can be regulated by controlling drying time, humidity, and temperature.

The volume of supply air should be sufficient to achieve the design condition. Airflow should be diffused or distributed to avoid objectionable drafts. Apart from causing personnel discomfort, drafts can cause dust problems and disturb the surface temperature uniformity of drying drums and other heated equipment. Supply and return air openings should be properly positioned (1) for good mixing and dilution of the room air, (2) to ensure efficient removal of fugitive vapors, and (3) to avoid short-circuiting of supply air into return or exhaust air openings. For automated processing equipment, tempered outside air should be supplied from the ceiling above the feed or head end of the machine at a minimum rate of 150 cfm per machine (Figure 1). If the machine extends through a wall into another room, both rooms need to be exhausted.

An exhaust system should be installed to remove humid or heated air and chemical vapors directly to the outside of the building (process streams typically must comply with regulations pursuant to the Clean Air Act). The room air from an open machine or tank area should be exhausted to the outdoors at a rate sufficient to achieve at least the vapor dilution levels recommended by the American Conference of Governmental Industrial Hygienists (ACGIH 2004). An exhaust rate higher than the supply rate produces a negative pressure and makes the escape of vapors or gases to adjoining rooms less likely. Depending on the process chemistry, local exhaust hoods may be needed at uncovered stabilizer tanks or at the bleach fix tanks (Figure 1). The exhaust opening should be positioned so that the flow of exhausted air is away from the operator, as illustrated in Figure 2. This air should not be recirculated. The exhaust opening should always be as close as possible to the source of the contaminant for efficient removal [see ACGIH (2004) for more information]. For a processing tank, the exhaust hood should have a narrow opening at the back of, level with, and as wide as the top edge of the tank.

Processing tanks are often covered to reduce evaporation of heated processing chemical solutions (approximately 100°F).

Covers on photographic processing equipment and chemical storage tanks can effectively minimize the amount of gases, vapors, or mists that enter the work area. If the processing tanks are enclosed and equipped with an exhaust connection, the minimum room air supply and exhaust rates may be reduced compared to an open tank (Figure 3).

A sulfide-toning sink should have a local exhaust hood to vent hydrogen sulfide. However, sulfide toners are rarely used now except for some specialized art processing and archival microfilm processing. The exhaust duct must be placed on the side opposite the operator so that vapor is not drawn toward the operator's face.

Air distribution to the drying area must provide an acceptable environment for operators as discussed in Chapter 8 of the 2005 *ASHRAE Handbook—Fundamentals* and ACGIH (2004). Exposed sides of the dryer should be insulated as much as is practical to reduce the large radiant and convected heat gain to the space. Exhaust grilles above the dryer can directly remove much of its rejected heat and moisture. Supply air should be directed to offset the remaining radiant heat gain to the space.

Using processor dryer heat to preheat cold incoming air during winter conditions can save energy. An economic evaluation is necessary to determine whether the energy savings justify the additional cost of the heat recovery equipment.
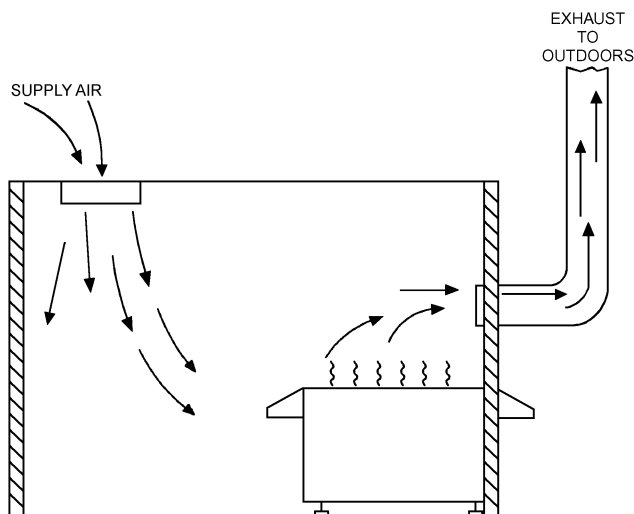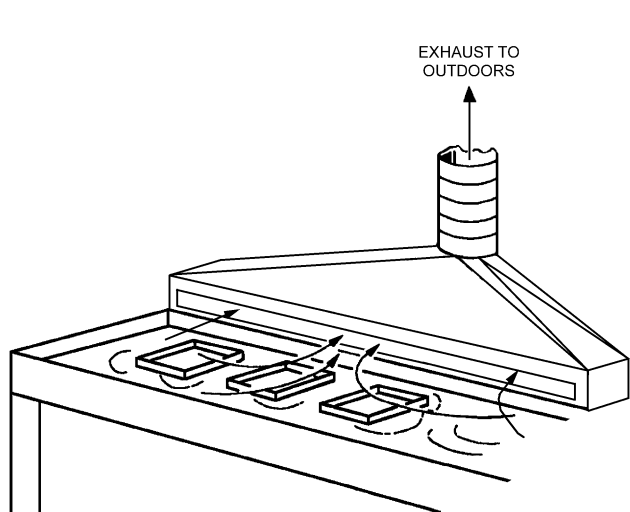
A canopy exhaust hood over the drying drum of continuous paper processors extracts heat and moisture. It is important to follow the processing equipment manufacturer's recommendations for venting the dryer section of the processor. Whenever possible, dryer vents should be exhausted to the outside of the building to prevent build-up of excessive temperature and humidity in the workplace.

When drying motion picture film, exhaust should draw off vapor from the solvent and wax mixture that is normally applied for lubrication.

Air Conditioning for the Printing/Finishing Operation

In printing, where a second sensitized product is exposed through the processed original, the amount of environmental control needed depends on the size and type of operation. For small-scale printing, close control of the environment is not necessary, except to minimize dust. In photofinishing plants, printers for colored products emit substantial heat. The effect on the room can be reduced by removing the lamphouse heat directly. Computer-controlled electronic printers transport the original film and raw film or paper at high speed. Proper temperature and humidity are especially important because, in some cases, two or three images from many separate films may be superimposed in register onto one film. For best results, the printing room should be maintained at between 70 and 75°F and at 50 to 60% rh to prevent curl, deformation, and static. Curl and film deformation affect the register and sharpness of the images produced. Static charge should be eliminated because it leaves static marks and may also attract dust to the final product.

Mounting of reversal film into slides is a critical finishing operation requiring a 70 to 75°F db temperature with 50 to 55% rh.

Digital printing operations use equipment that generates significant heat. An exhaust system can be directly connected to the laser printer to remove heat at a flow rate specified by the equipment manufacturer. Sufficient room ventilation is required so that applicable occupational exposure limits are not exceeded and a favorable operating environment is maintained.

Particulates in Air

Air conditioning for most photographic operations requires 85% efficiency disposable bag-type filters with 30% efficiency prefilters to extend the bag filter life. In critical applications (such as high-altitude aerial films) and for microminiature images, filtering of foreign matter is extremely important. These products are handled in a laminar airflow room or workbench with 95% efficiency HEPA filters plus 30% efficiency disposable prefilters.

Fig. 1   Open Machine Ventilation

Fig. 2   Open-Tray Exhaust Ventilation from Processing Sink
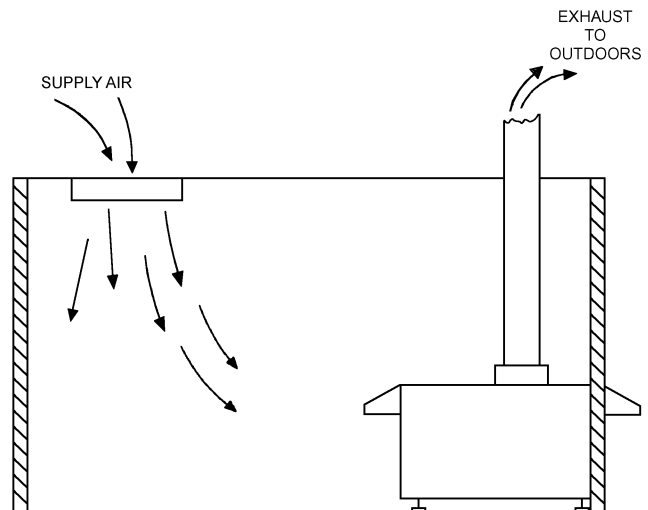
Fig. 3   Enclosed Machine Ventilation

Other Exhaust Requirements

A well-ventilated room should be provided for mixing the chemicals used in color processing and high-volume black-and-white work. The room should be furnished with movable exhaust hoods that provide a capture velocity as defined in the ACGIH (2004) *Industrial Ventilation Manual* for the worst-case scenario. Modern photographic minilabs often use canisters of premixed processing solutions, so no chemical mixing is necessary.

If prints are lacquered regularly, a spray booth is needed. Concentrated lacquer spray is both hazardous and very objectionable to personnel; spray booth exhaust must be discharged outside.

Processing Temperature Control

Low processing volumes are typically handled in minilabs, which are often installed in retail locations. Minilabs are usually self-contained and equipped with temperature controls, heaters, and pumps. Typically, the owner only has to connect the minilab to water, electricity, exhaust (thimble connection), and a drain.

Higher-volume processing is handled with processors that come from the manufacturer complete with controls, heat exchangers, pumps, and control valves designed for the process that the owner has specified. Electricity, hot water, cold water, drainage, and steam may be required, depending on the manufacturer, who typically provides the specifications for these utilities.

STORING PROCESSED FILM AND PAPER

Storage of developed film and paper differs from storage of raw stock, because the developed materials are no longer photosensitive, are seldom sealed against moisture, and are generally stored for much longer periods. Required storage conditions depend on (1) the value of the records, (2) length of storage time, (3) whether the films are on nitrate or safety base, (4) whether the paper base is resin coated, and (5) type of photographic image.

Photographic materials must be protected against fire, water, mold, chemical or physical damage, high relative humidity, and high temperature. Relative humidity is much more critical than temperature. High relative humidity can cause films to stick together, (particularly roll films, but also sheet films). High humidity also damages gelatin, encourages the growth of mold, increases dimensional changes, accelerates the decomposition of nitrate support, and accelerates the deterioration of both black-and-white and color images. Low relative humidity causes a temporary increase in curl and decrease in flexibility, but when the humidity rises again, these conditions are usually reversed. An exception occurs when motion picture film is stored for a long time in loosely wound rolls at very low humidities. The curl causes the film roll to resemble a polygon rather than a circle when viewed from the side. This **spokiness** occurs because a highly curled roll of film resists being bent in the length direction when it is already bent in the width direction. When a spoky roll is stored for a long time, the film flows permanently into the spoky condition, resulting in film distortion. Very low relative humidity in storage may also cause the film or paper to crack or break if handled carelessly.

Low temperature (–10 to 50°F) is desirable for film and paper storage if (1) the relative humidity of the cold air is controlled, and (2) the material can be sufficiently warmed (for 2 to 8 h) before opening to prevent moisture condensation. High temperature can accelerate film shrinkage, which may produce physical distortions and the fading of dye images. High temperature is also detrimental to the stability of nitrate film.

Film Longevity

The American National Standards Institute (ANSI *Standard* IT9.11) defines longevities of films with a life expectancy (LE) rating. The **LE rating** is the minimum number of years information can be retrieved if the subject film is stored under long-term storage conditions. In order to achieve the maximum LE rating, a product must be stored under long-term storage conditions. Polyester black-and-white silver gelatin films have an LE rating of 500, and acetate black-and-white silver gelatin films have an LE rating of 100. No LE ratings have been assigned to color films or black-and-white silver papers. Medium-term storage conditions have been defined for materials that are to retain their information for at least 10 years.

Medium-Term Storage

Rooms for medium-term storage of safety base film should be protected from accidental water damage by rain, flood, or pipe leaks. Air conditioning with controlled relative humidity is desirable but not always essential in moderate climates. Extremes of relative humidity are detrimental to film.

The most desirable storage relative humidity for processed film is about 50%, although 30 to 60% is satisfactory. Air conditioning is required where the relative humidity of the storage area exceeds 60% for any appreciable period. For a small room, a dehumidifier may be used if air conditioning cannot be installed. The walls should be coated with a vapor retarder, and the controlling humidistat should be set at about 40% rh. If the prevailing relative humidity is under 25% for long periods and problems from curl or brittleness are encountered, humidity should be controlled by a mechanical humidifier with a controlling humidistat set at 40%.

For medium-term storage, a room temperature between 68 and 77°F is recommended. Higher temperatures may cause shrinkage, distortion, and dye fading. Occasional peak temperatures of 95°F should not have a serious effect. Color films should be stored below 50°F to reduce dye fading. Films stored below the ambient dew point should be allowed to warm up before being opened to prevent moisture condensation.

An oxidizing or reducing atmosphere may deteriorate the film base and gradually fade the photographic image. Oxidizing agents may also cause microscopically small colored spots on fine-grain film such as microfilm (Adelstein et al. 1970). Typical gaseous contaminants include hydrogen sulfide, sulfur dioxide, peroxides, ozone, nitrogen oxides, and paint fumes. If these fumes are present in the intended storage space, they must be eliminated, or the film must be protected from contact with the atmosphere.

Long-Term Storage

For films or records that are to be preserved indefinitely, long-term storage conditions should be maintained. The recommended space relative humidity ranges from 20 to 50% rh, depending on the film type. When several film types are stored within the same area, 30% rh is a good compromise. The recommended storage temperature is below 70°F. Low temperature aids preservation, but if the storage temperature is below the dew point of the outside air, the records must be allowed to warm up in a closed container before they are used, to prevent moisture condensation. Temperature and humidity conditions must be maintained year-round and should be continuously monitored.

Requirements of a particular storage application can be met by any one of several air-conditioning equipment combinations. Standby equipment should be considered. Sufficient conditioned outside air should be provided to keep the room under a slight positive pressure for ventilation and to retard the entrance of untreated air. The air-conditioning unit should be located outside the vault for ease of maintenance, with precautions taken to prevent water leakage into the vault. The conditioner casing and all ductwork must be well insulated. Room conditions should be controlled by a dry-bulb thermostat and either a wet-bulb thermostat, humidistat, or dewpoint controller.

Air-conditioning installations and fire dampers in ducts carrying air to or from the storage vault should be constructed and maintained according to National Fire Protection Association (NFPA)

recommendations for air conditioning (NFPA *Standard* 90A) and for fire-resistant file rooms (NFPA *Standard* 232).

All supply air should be filtered with noncombustible HEPA filters to remove dust, which may abrade the film or react with the photographic image. As with medium-term storage, gaseous contaminants such as paint fumes, hydrogen sulfide, sulfur dioxide, peroxides, ozone, and nitrogen oxides may cause slow deterioration of the film base and gradual fading of the photographic image. When these substances cannot be avoided, an air scrubber, activated carbon adsorber, or other purification method is required.

Films should be stored in metal cabinets with adjustable shelves or drawers and with louvers or openings located to facilitate circulation of conditioned air through them. The cabinets should be arranged in the room to permit free circulation of air around them.

All films should be protected from water damage due to leaks, fire sprinkler discharge, or flooding. Drains should have sufficient capacity to keep the water from sprinkler discharge from reaching a depth of 3 in. The lowest cabinet, shelf, or drawer should be at least 6 in. off the floor and constructed so that water cannot splash through the ventilating louvers onto the records.

When fire-protected storage is required, the film should be kept in either fire-resistant vaults or insulated record containers (Class 150). Fire-resistant vaults should be constructed in accordance with NFPA *Standard* 232. Although the NFPA advises against air conditioning in valuable-paper record rooms because of the possible fire hazard from outside, properly controlled air conditioning is essential for long-term preservation of archival films. The fire hazard introduced by the openings in the room for air-conditioning ducts may be reduced by fire and smoke dampers activated by smoke detectors in the supply and return ducts.

Storage of Cellulose Nitrate Base Film

Although photographic film has not been manufactured on cellulose nitrate (nitrocellulose) film base for several decades, many archives, libraries, and museums still have valuable records on this material. Preserving the cellulose nitrate film will be of considerable importance until the records have been printed on safety base.

Cellulose nitrate film base is chemically unstable and highly flammable. It decomposes slowly but continuously even under normal room conditions. The decomposition produces small amounts of nitric oxide, nitrogen dioxide, and other gases. Unless the nitrogen dioxide can escape readily, it reacts with the film base, accelerating the decomposition (Carrol and Calhoun 1955). The rate of decomposition is further accelerated by moisture and is approximately doubled with every 10°F increase in temperature.

All nitrate film must be stored in an approved vented cabinet or vault. Nitrate films should never be stored in the same vault with safety base films because any decomposition of the nitrate film will cause decomposition of the safety film. Cans in which nitrate film is stored should never be sealed, because this traps the nitrogen dioxide gas. Standards for storing nitrate film have been established (NFPA *Standard* 40). The National Archives and the National Institute of Standards and Technology have also investigated the effect of a number of factors on fires in nitrate film vaults (Ryan et al. 1956).

The storage temperature should be kept as low as economically possible. The film should be kept at less than 50% rh. Temperature and humidity recommendations for the cold storage of color film in the following section also apply to nitrate film.

Storage of Color Film and Prints

All dyes fade in time. ANSI *Standard* IT9.11 does not define an LE for color films or black-and-white images on paper. However, many valuable color films and prints exist, and it is important to preserve them for as long as possible.

Light, heat, moisture, and atmospheric pollution contribute to fading of color photographic images. Storage temperature should be as low as possible to preserve dyes. For maximum permanence of images, materials should be stored in light-tight sealed containers or in moisture-proof wrapping materials at a temperature below freezing and at a relative humidity of 20 to 50%. The containers should be warmed to room temperature before opening to avoid moisture condensation on the surface. Photographic films can be brought to the recommended humidity by passing them through a conditioning cabinet with circulating air at about 20% rh for about 15 min.

An alternative is the use of a storage room or cabinet controlled at a steady (noncycled) low temperature and maintained at the recommended relative humidity. This eliminates the necessity of sealed containers, but involves an expensive installation. The dye-fading rate decreases rapidly with decreasing storage temperature.

Storage of Black-and-White Prints

The recommended storage conditions for processed black-and-white paper prints should be obtained from the manufacturer. The optimum limits for relative humidity of the ambient air are 30 to 50%, but daily cycling between these limits should be avoided.

A variation in temperature can drive relative humidity beyond the acceptable range. A temperature between 59 and 77°F is acceptable, but daily variations of more than 7°F should be avoided. Prolonged exposure to temperatures above 86°F should also be avoided. The degradative processes in black-and-white prints can be slowed considerably by low storage temperature. Exposure to airborne particles and oxidizing or reducing atmospheres should also be avoided, as mentioned for films.

Storage of Digital Images

A hard drive should only be used for temporary storage, because if that drive fails, the images could be lost forever. Digital files should be backed up on alternative media (e.g., CD-ROMs) for short-term storage. Because of rapid technological development, storage media systems in 10 to 20 years may not be compatible with current CD-ROMs. In addition, CDs are somewhat fragile and susceptible to damage and data loss if not handled properly. Digital images can be stored as photographic prints; these can last for generations when stored properly as described in the preceding sections.

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CHAPTER 21

MUSEUMS, GALLERIES, ARCHIVES, AND LIBRARIES

UNDERSTANDING and appreciating humanity's diverse cultures and history dictates preserving artifacts ranging from books and documents to artwork, historical artifacts, technological accomplishments, specimens of national history, examples of popular culture, and once-common trade goods. Their importance ranges from national to regional or even local, but their symbolic and aesthetic values give them monetary worth frequently impossible to estimate. Thus, their preservation is worthwhile and may even be legally mandated. The loss of any one of these artifacts is a loss to all individuals.

Historical collections are vulnerable to many threats. Because they must be preserved indefinitely, the steps taken to protect them are sometimes extraordinary. Most threats can be addressed by properly maintained housing, with professional support. The level of acceptable risk is a compromise between the theoretically ideal environment and the practical. It is possible to slow deterioration drastically, but doing so undermines the ultimate function of museums, libraries, and archives: not only to preserve, but also to allow public and scholarly access. Additionally, extremely high control over all environmental parameters can ensure an object's survival, but at a price no cultural institution can justify or is willing to pay. Managing risk, not avoiding it altogether, is the objective.

This chapter addresses threats to collections that are minimized by a well-designed HVAC system that provides stability for low-access storage environments and also serves high-traffic visitors' areas.

Theoretically, many systems can successfully provide environmental control, if properly applied. From project inception, both the design objective and realistically available operation and maintenance resources must be considered.

Communication with the client is especially critical when designing systems for museums, galleries, archives, and libraries because of the uniqueness of the criteria: the inherent risk associated with environmental conditions. The design team must include not only museum administrators but also collections' managers, curators, conservators, and security. Administrators are responsible for fiscal decisions, whereas the collection managers are responsible for care of the collection. Curators build the collection and design exhibitions. Conservators are charged with preservation of the collection. Security staff is critical to safekeeping of the collection. Many HVAC system design decisions are based on the needs of the collection and the use of the various spaces. To design the best system, all relevant parties must be part of the process. This chapter can only explain why temperature, humidity, light, and indoor air quality (IAQ) requirements are critical; the team must decide the exact specifications.

This chapter focuses on relative humidity, temperature, and air pollution design for HVAC systems, and describes various systems that are applicable for these spaces. The goal is to illustrate special

needs of collection spaces in museums, galleries, archives, and libraries. See the References and Bibliography for additional resources.

Note that this chapter does not apply to libraries designed for public access, with collections that are not intended for archival preservation. These facilities may include collections designed for general public use or school-aged children, and may have significant quantities of electronic documents in disk format or tape. The types of controls (humidity, thermal, or particulate and molecular phase filtration) required for collections of archival preservation are not practical for these facilities (see Chapter 3 for additional information).

In nonarchival libraries, there may be no HVAC system, or the HVAC systems may be designed specifically for human comfort during occupied hours. In this application, the HVAC systems may shut off during unoccupied or low-occupancy times for energy savings.

This chapter may not apply and should be bypassed if one or more of the following conditions exist with the scope of design for a library (see Chapter 3 for additional information):

- HVAC system is cycled off during unoccupied periods
- HVAC system is turned off seasonally
- HVAC system is designed to cycle on/off with thermal satisfaction alone
- Natural ventilation is the only method of air circulation

General Factors Influencing Damage

In designing HVAC systems for collections, a good working relationship between the mechanical engineer, architect, interior designer, and owner/operator, especially client personnel responsible for preserving the collection, is critical. All limitations must be defined at the beginning of the design.

Artifacts and collections can be of one material (e.g., an archive of antique books), which simplifies target specifications, or combinations of materials with different levels of instability (e.g., a multimedia library that includes both books and film); in the latter case, target conditions are usually a compromise. For more details, see Michalski (1996a).

The building's architecture and mechanical systems need to manage eight types of threats to collections; mechanical engineers need to appreciate and respect these concerns even if they do not appear to relate directly to a building's mechanical systems. Respecting all the risks gives the client an increased comfort zone for threats the HVAC system is designed to specifically control. The following threats, in decreasing order of seriousness, affect all types of collections.

Light damage is perhaps the most extensive threat to museum collections. Most materials undergo some form of undesirable, permanent photochemical or photophysical change from overexposure to light. It is, however, relatively easy to control at the architectural, design, and operational levels by eliminating ultraviolet light, limiting illumination intensity, and restricting total illumination duration.

The preparation of this chapter is assigned to TC 9.8, Large Building Air-Conditioning Applications.

Table 1 Classification of Rooms for Museums and Libraries

		High Internal Source of Contaminants (Dirty)	Low Internal Source of Contaminants (Clean)
Collection	Non-public access	Conservation laboratories, museum workshops (VOCs, fumes, dusts) "Wet" collections (alcohol or formaldehyde evaporation from poorly sealed jars in natural history collections) Photographic collections ("vinegar syndrome" produces acetic acid vapors)	Most storage areas, vaults, library stacks
	Public access	Displays of conservation work in progress (unusual and temporary)	Galleries, reading rooms
Noncollection	Non-public access	Smoking offices (unusual)	Offices (nonsmoking)
	Public access	Cafeterias, rest rooms, spaces where smoking permitted	Public spaces without food preparation or smoking Some public and school library stacks and reading rooms

Relative humidity also presents a risk. For each material, there is a level of environmental moisture content (EMC) consistent with maximum chemical, physical, or biological stability. When the EMC is significantly too low or too high, the associated relative humidity becomes a risk factor. Recent literature often calls humidity-related damage "incorrect relative humidity" to emphasize the concept of ranges of acceptable moisture content rather than absolute limits.

Temperature ranges for materials must also be controlled. Some polymers become brittle and are more easily fractured when the temperature is too low. At temperatures that are too high, damaging chemical processes accelerate. Thermal energy not only accelerates aging, but also can magnify the effects of incorrect relative humidity. Therefore, incorrect relative humidity and temperature are often taken together when deciding ideal parameters for important classes of materials such as for paper and photography. Any temperature change also changes the relative humidity. Therefore, careful and close control of relative humidity requires temperature control in the same magnitude of importance.

Air pollution includes outdoor-generated gaseous and particulate pollutants that infiltrate the building, as well as indoor-generated ones. Even very low levels of contaminants can adversely affect the condition of collections. Particulate filtration to control both coarse and fine particles and gaseous filtration are discussed in the System Selection and Design section.

Pest infestation primarily includes insects consuming collections for food; mold, fungi, and bacteria also qualify as pests, but they can be limited by controlling relative humidity, temperature, indoor air quality, and ventilation.

Shock and **vibration** can cause long-term damage to sensitive objects. Vibration can be transmitted to objects by service vehicles during packing and shipping. Usually, HVAC design only needs to consider this risk if vibration is transmitted through ductwork to works hung on adjacent walls or in particularly active air drafts. Additionally, excess vibration could potentially lead to objects vibrating off of exhibit and/or storage shelves.

Natural emergencies are, fortunately, rare, and most institutions have (or should have) emergency response policies. However, avoidable emergencies could result from building and mechanical design malfunctions such as water pipe failure, especially over collections and storage facilities. The infrequency of these failures leads many to forget that just one failure, however rare, could ruin a significant portion of a collection. Every effort should be made to route water lines and other utilities away from areas that house irreplaceable objects. Building systems also rely on the infrastructure to provide utilities and communications. Where the infrastructure is not reliable or of adequate capacity, provisions should be made for temporary or alternative supply.

Theft, **vandalism**, and **misplacing objects** can be addressed by limiting access to mechanical systems to improve security.

This chapter focuses on relative humidity, temperature, and air pollution design for HVAC systems. Many excellent books treat the subject of environmental management in museums and libraries extensively; consult the References and Bibliography for information not contained in this chapter.

ENVIRONMENTAL EFFECTS ON COLLECTIONS

DETERMINING PERFORMANCE TARGETS

Museums, archives, and libraries have two categories of indoor air requirements: general health and safety, comfort, and economy of operation as listed in ASHRAE *Standards* 55 and 62.1; and the collections' requirements, which are not yet completely understood, and often conflict across collection types. The risk of compromising on relative humidity and temperature specifications must be assessed. The following sections summarize the best information on these issues.

In terms of health and safety and the collection's requirements, building spaces can be categorized as shown in Table 1: (1) collection versus noncollection, (2) public versus nonpublic, and (3) "dirty" versus "clean." These subdivisions distinguish between areas that have very different thermal and indoor air quality requirements, outdoor ventilation rates, air supply strategies, etc. These areas often require separate HVAC systems. See Chapters 14, 29, and 30 for more information on dirty rooms. Noncollection rooms are not considered in this chapter because their HVAC requirements are similar to those in other public buildings, as discussed in Chapter 3.

The following sections provide a framework for developing appropriate climate and indoor air quality (IAQ) parameters for different museums, libraries, and archives. A single target is a compromise between large numbers of different, often contradictory requirements. However, many collections are uniform enough to allow useful generalizations to be made about their HVAC requirements. In this chapter, the term "effective" includes institutional value judgments as well as the science of deterioration (Michalski 1996b).

Temperature and Humidity

Current Standards. The classic reference for conservation professionals is Thomson's (1994) *The Museum Environment.* Set points of 50% rh and 68°F were listed as an example for temperate climates and unfortunately taken as ideal (in the United States, 68°F was frequently rounded up to 70°F). Misuse is a danger associated with listing standards or settings: numbers in a table can be extracted or used without understanding the associated text. This is why the parameters in this chapter are presented for different classifications of collections or building types. Environmental settings should be determined for collection types and must consider the climate zone where building is located. Photographic collections in the Pacific Northwest have different needs than porcelain in equatorial regions. The design engineer cannot be expected to know the needs

of the collection, but can consult the other members of the team, especially the conservators, collection managers, and curators. Ideal set points are a compromise between comfort for museum visitors and staff and the minimum temperature and relative humidity for the collection.

Davis (2006) reports that decreasing temperature from 70 to 65°F and relative humidity from 50 to 45% significantly increases expected lifetime. A useful tool to measure aging rates or deterioration rates is the Preservation Calculator created by the Image Permanence Institute (IPI 2006), which can be downloaded for free from the IPI Web site at http://www.imagepermanenceinstitute.org/shtml_sub/dl_prescalc.shtml. This software calculates the **preservation index (PI)**, which expresses the preservation quality of a storage environment for organic materials. It is a useful tool to understand the effects of temperature and relative humidity on natural aging of organic collections. Comparing the former "ideal" set points (70°F and 50% rh) with current recommended parameters (65°F and 45% rh), the PI increases from 39 to 64 years, or 64%. IPI also developed software that includes a more sophisticated preservation calculator and takes into account collection types, light, and more.

Biological Damage. Dampness accelerates mold growth on most surfaces, corrosion of base metals, and chemical deterioration in most organic materials. Of all HVAC-controllable environmental parameters, high humidity is the most important factor.

The most comprehensive mold data are from the feed and food literature. Fortunately, this provides a conservative outer limit to dangerous conditions. Mold on museum objects occurs first on surfaces contaminated with sugars, starch, oils, etc., but can also occur on objects made of grass, skin, bone, and other feed- or food-like materials. Water activity is identical to and always measured as the equilibrium relative humidity of air adjacent to the material. This provides a better measure than the EMC for mold germination and growth on a wide variety of materials (Beuchat 1987). Figure 1 shows the combined role of temperature and relative humidity. The study of the most vulnerable book materials by Groom and Panisset (1933) concurs with the general trend of culture studies from Ayerst (1968). Ohtsuki (1990) reported microscopic mold occurring on clean metal surfaces at 60% rh. The DNA helix is known to collapse near 55% rh (Beuchat 1987), so a conservative limit for no mold ever, on anything, at any temperature, is below 60% rh. Chapter 23 suggests a similar lower boundary for mold in food crops.

Snow et al. (1944) looked for visible mold growth on materials inoculated with a mixture of mold species. These are plotted in Figure 2, and follow the same trend reported by Hens (1993) for the European building industry for wall mold.

Figures 1 and 2 show practical dangers: growth in less than a summer season requires over 70% rh, and growth in less than a week requires over 85% rh.

For both collection and occupant health, and given the need in museums to humidify air more than many applications in winter, care must be taken to avoid cold surfaces where condensation might occur, such as on windows and ductwork.

Rapid corrosion above 75% rh occurs for two reasons: increased surface adsorption of water, and contamination by salts. Water adsorption on clean metal surfaces climbs rapidly from 3 molecules or less below 75% rh to bulk liquid layers above 75% rh (Graedel 1994). This phenomenon is aggravated by most surface contaminants, as shown in studies of the role of dust on clean steel corrosion. The most common contaminant of museum metals, sodium chloride, dissolves and liquefies (deliquesces) above 76% rh.

Mechanical Damage. Very low or fluctuating relative humidity or temperature can lead to mechanical damage of artifacts. The fundamental cause is expansion and contraction of materials, combined with some form of internal or external restraint. Very low humidity or temperature also increases the stiffness of organic materials, making them more vulnerable to fracture. Traditionally,

ASSUMES RH HAS CLIMBED, NOT FALLEN, TO THESE VALUES.
BOOK MATERIALS: GROOM AND PANISSET (1933)
BORDER CURVE: SUMMARY OF CULTURE STUDIES IN AYERST (1968)

○ OLD PARCHMENT
△ STARCHED COTTON
□ GOAT SKIN
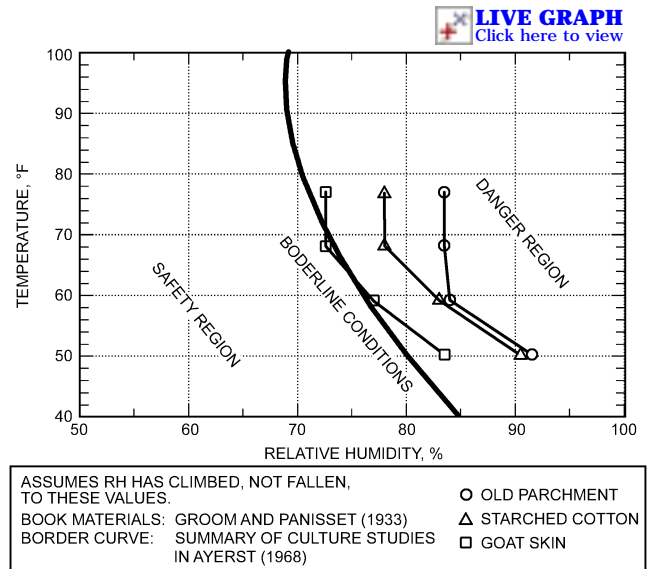
Fig. 1 Temperature and Humidity for Visible Mold in 100 to 200 days

ASSUMES HIGHLY SUSCEPTIBLE MATERIAL AT ABOUT 75°F, AND RH HAS CLIMBED, NOT FALLEN, TO THESE VALUES.

DATA POINTS FROM SNOW ET AL. (1944)
+ no growth in 1300 days at 60% rh
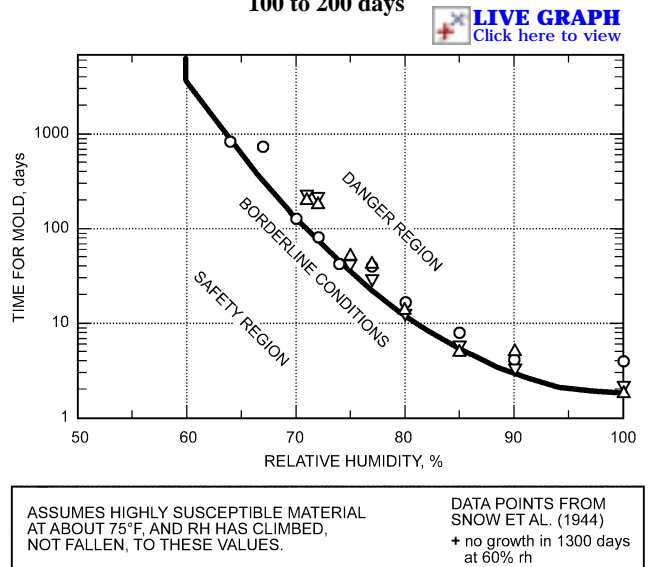
Fig. 2 Time Required for Visible Mold Growth

these concerns have led to extremely narrow specifications, such as 50 ± 3% rh and 70 ± 2°F (LaFontaine 1979), which still form the basis of many museum and archive guidelines. These specifications were extrapolated from the observation that very large fluctuations fractured some objects, but with no experimental or theoretical basis for precise extrapolation to smaller fluctuations.

Research on objects (Erhardt and Mecklenburg 1994; Erhardt et al. 1996; Erlebacher et al. 1992; Mecklenburg and Tumosa 1991; Mecklenburg et al. 1998, 2005; Michalski 1991, 1993), experience in historic-building museums, and comparison of historic buildings with and without air conditioning (Oreszczyn et al. 1994) led to reappraisal of these fluctuation specifications. Despite minor disagreement over interpretation, the practical conclusions are the same: the traditional very narrow tolerances exaggerated artifact needs. Between fluctuations of about ±10% rh with ±18°F and ±20% rh with ±36°F, risk of fracture or deformation climbs from insignificant to significant for a mixed historic collection, and climbs even more quickly for increasingly large fluctuations. The range of ±20 to 40% rh yielded common observations of cracked cabinetry and paintings.

Research models use a restrained sample of organic material (e.g., paint, glue, or wood) subjected to lowered relative humidity or temperature. The material both shrinks and stiffens. Daly and Michalski (1987) and Hedley (1988) collected consistent data on the increase in tension for traditional painting materials, and Michalski (1991, 1999) found consistent results with other viscoelastic data on paints and their polymers. For example, acrylic paintings do not increase in tension at low relative humidity nearly as much as traditional oil paintings. On the other hand, acrylic paints stiffen much more than oil paints between 70 and 41°F, greatly increasing acrylic paintings' vulnerability to shock and handling damage. The increase in material tension can be calculated as the modulus of elasticity times the coefficient of expansion integrated over the decrement in relative humidity or temperature. Each factor is a function of relative humidity and temperature (Michalski 1991, 1998; Perera and Vanden Eynde 1987). Mecklenburg et al. (2005) demonstrated that oil paints and acrylic paints are not adversely affected by low relative humidity but by low temperatures. Their research also shows that most oil paints shrink very little from 60 to 10% rh.

Modeling at the Smithsonian Institution used the material's yield point (i.e., nonrecoverable deformation) as a threshold criterion for damage, and hence permissible fluctuations (Erhardt and Mecklenburg 1994; Mecklenburg et al. 1998). From their data on expansion coefficients and tensile yield strain in wood, for example, they estimated a permissible relative humidity fluctuation of ±10% in pine and oak, greater for spruce. Modeling on paint and glue suggested ±15% rh as a safe range (Mecklenburg et al. 1994). More extensive data on compression yield stress across the grain are available for all useful species of wood in USDA (1999), which can be combined with elasticity data for that species and relative moisture content to obtain yield strain and yield relative humidity fluctuation. These vary widely but center near ±15% rh.

Alternative modeling at the Canadian Conservation Institute used fracture as the criterion for damage, and the general pattern of fatigue fracture in wood and polymers to extrapolate the effect of smaller multiple cycles (Michalski 1991). With a benchmark of high probability of single-cycle fracture at ±40%, known from observation of museum artifacts, fatigue threshold stress (10^7 cycles or more) can be extrapolated by an approximate factor of 0.5 in wood (±20% rh) and 0.25 in brittle polymers (±10% rh) such as old paint. This is consistent with the yield criterion: yield stress in these materials corresponds to stresses that cause very small or negligible crack growth per cycle. Researchers also noted that the coefficient of expansion in wood and other materials is minimized at moderate relative humidity because of sigmoidal adsorption isotherms, so fluctuations at lower and higher relative humidity set points tend to be even riskier.

Both models assume uniformly restrained materials. As a first approximation, many laminar objects (e.g., paintings on stretchers, photographic records) fall in this class. Artifacts, however, tend to be complex assemblies of materials. Some are less vulnerable because of lack of restraint (e.g., floating wood panels, books or photographs with components that dilate in reasonable harmony); other assemblies contain sites of severe stress concentration that initiate early fracture. Michalski (1996b) classifies vulnerability for wooden objects as very high, high, medium (uniformly restrained components), and low. Each category differs from the next lower one by a factor of two (i.e., half the relative humidity fluctuation causes the same risk of damage).

Chemical Damage. Higher temperatures and moderate amounts of adsorbed moisture lead to rapid decay in chemically unstable artifacts, especially some archival records. The most important factor for modern records is acid hydrolysis, which affects papers, photographic negatives, and magnetic media (analog and digital). Sebor (1995) developed a graphical format for relating these two parameters to lifetime for book papers. An improved graphical representation is shown in Figure 3. Fortunately for HVAC design purposes, the
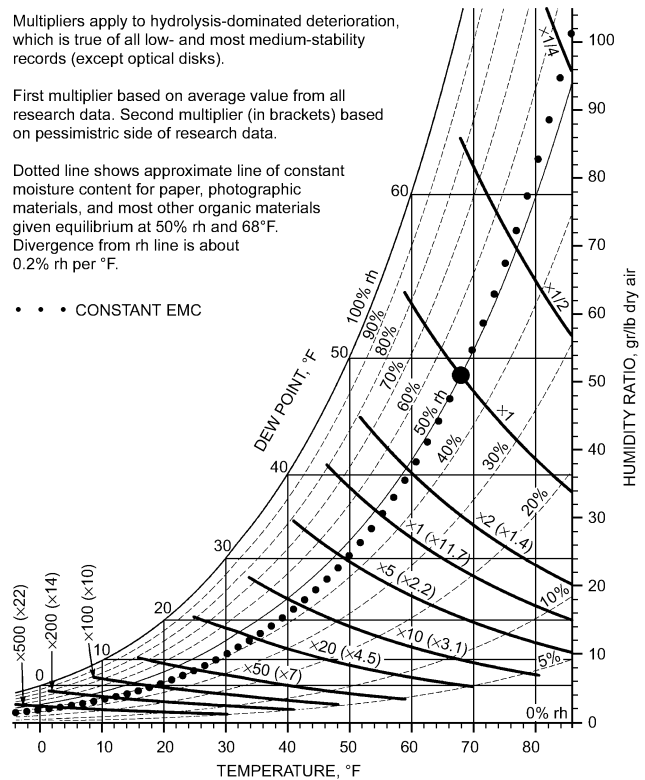
Fig. 3   Lifetime Multipliers Relative to 68°F and 50% rh

dependence on relative humidity and temperature in all records is very similar. Although the precise quantification and meaning of record lifetime is debatable, all authorities agree that the most rapidly decaying records (e.g., videotapes, acidic negatives) can become unstable within a few decades at normal room conditions, and much faster in hot, humid conditions. Figure 3 shows the relative increase in record lifetime under cold, dry conditions; the range in numbers on each line reflects the spread in available data. Extension of the plots below 5% rh is uncertain; rates of chemical decay may or may not approach zero, depending on slow, nonmoisture-controlled mechanisms such as oxidation.

Lifetime improvement predictions for photographic data were devised by the Image Permanence Institute (Nishimura 1993; Reilly 1993) and implemented in a lifetime prediction wheel. These relative lifetime estimates are less optimistic about improvement with low relative humidity, but the general trend is the same as the Michalski plots. The Image Permanence Institute has developed a new data logger capable of displaying an integrated permanence index for organic materials with activation energies for aging similar to archival record paper.

Critical Relative Humidity

At some critical relative humidity, some minerals hydrate, dehydrate, or deliquesce. When part of a salt-containing porous stone, a corroded metal, or a natural history specimen, these minerals disintegrate the object. Distinct critical relative humidity values are known for dozens of minerals in natural history collections (Waller 1992). Pyrites, which contaminate most fossils, disintegrate if held above 60% rh (Howie 1992). Bronze, one of the most important archaeological metals, has a complex chemistry of corrosion, with several critical relative humidity values (Scott 1990). This variety means there is no universal safe relative humidity; particular conditions should be achieved for specific artifacts with local cabinets or small relative-humidity-controlled packages (Waller 1992). The only generalization is that anything over 75% rh is dangerous.
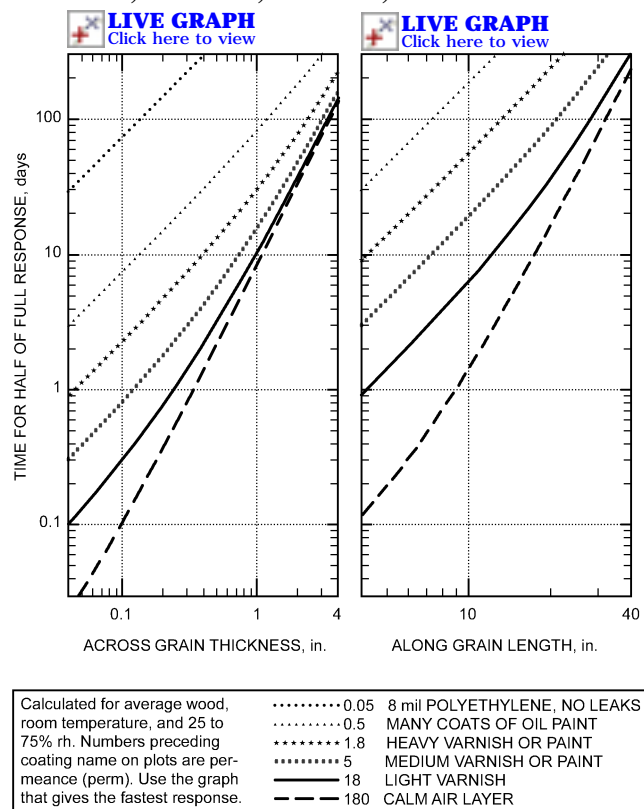
Fig. 4 Calculated Humidity Response Times of Wooden Artifacts
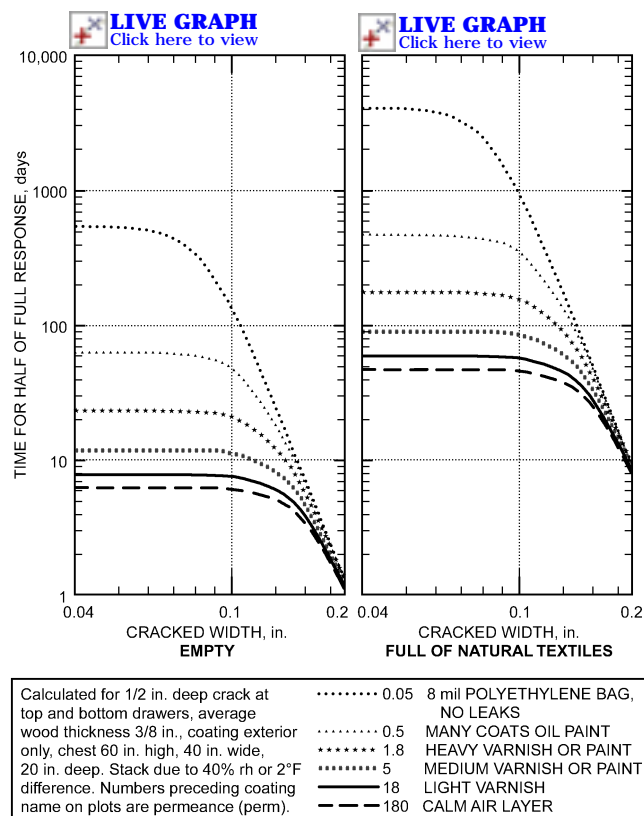
Fig. 5 Interaction of Air Leakage, Wood Coating, and Textile Buffering on Response of Wooden Chest of Drawers

Response Times of Artifacts

Brief relative humidity fluctuations may not affect artifacts; very few museum objects respond significantly to fluctuations under an hour in duration. Hence, a 15 min cycle in HVAC output does not affect most artifacts, unless it is so large as to cause sudden damp conditions. Many objects take days to respond. Figure 4 shows calculated humidity response times of wooden artifacts. Figure 5 shows the interaction of air leakage, wood coatings, and textile buffering on the response of a chest of drawers; risk increases if the piece is displayed empty and open, rather than closed and full, because response time falls from months to days.

Very long fluctuations, such as seasonal changes, are slow enough to take advantage of stress relaxation in artifact components. Data on the effective modulus of elasticity of many oil and acrylic paints as a function of time, temperature, and relative humidity (Michalski 1991) and direct stress relaxation data for both paint (Michalski 1995) and wood imply that stress caused by a given strain applied over 1 day falls to 50% or less if that stress is applied over 4 months at moderate room temperatures. Thus, a 4 month seasonal ramp of ±20% rh should cause less stress in most artifacts than a 1 week fluctuation of ±10 rh.

AIRBORNE POLLUTANTS

Research shows that gaseous outdoor pollutants can easily penetrate all types of buildings, including modern HVAC-equipped construction, when no chemical filtration exists to remove them (Cass et al. 1989; Davies et al. 1984; Druzik et al. 1990). Particle intrusion from outside sources has also been well documented in art museums (Brimblecombe 1990; Nazaroff et al. 1993; Yoon and Brimblecombe 2001).

Collections can themselves be sources of airborne pollutants (Grzywacz and Gailunas 1997). Collections with leather, fur, and wood elements can release reduced sulfides, aldehydes, carboxylic acids, or fatty acids. These contaminants may instigate or accelerate deterioration of other artifacts. Acetic acid emitted from degrading cellulose acetate films is another good example. In general, the major risks to collections from indoor-generated pollutants are from acetic and formic acids [one precursor of which is formaldehyde (Raychaudhuri and Brimblecombe 2000), which must also be controlled]. These gases are emitted from wood and wood-based materials as well as adhesives, finishing products, etc. Reduced sulfides (e.g., hydrogen sulfide and carbonyl sulfide) can be released from wools and silks (Brimblecombe et al. 1992; Watts 1999).

During construction or renovation at the building, room, or display case levels, high amounts of suspended particles (often including mold spores and vapors) are generated. Depending on the HVAC system, airborne pollutant concentrations may not reduce to acceptable levels for a few weeks up to several months after work is finished (Eremin and Tate 1999; Grzywacz 2006). Adhesives, coatings, and sealants initially release high levels of pollutants. In poorly ventilated enclosures or rooms, emission rates may be retarded because of equilibrium vapor pressures. Fortunately, levels of pollutants released by wet products in well-ventilated rooms usually decrease rapidly, though carboxylic acid emitted by alkyd or oil-based coatings decreases at a much slower rate (Chang et al. 1998; Fortmann et al. 1998). Even after emissions level off, the amount of acids released by these coatings can remain unsatisfactory for several years, even in ventilated rooms. Food preparation and service vehicles are also sources of contaminants, and require special consideration. The source of outside air for the HVAC system, especially intakes that deliver to collections, is important.

Sources of Airborne Pollutants

Of the hundreds of air pollutants, only a few have been identified as dangerous for collections in museums and archives. Table 2 lists major airborne pollutants, their typical sources, and materials at

Table 2 Major Gaseous Pollutants of Concern to Museums, Galleries, Archives, and Libraries: Sources and At-Risk Materials

Gaseous Pollutants[a]	Major Sources and Some Important Minor Sources	At-Risk Materials
	Important Inorganic Pollutants	
Sulfur dioxide (SO$_2$) Sulfur dioxide can react with water vapor in the air and form both **sulfurous acid (H$_2$SO$_3$)** and **sulfuric acid (H$_2$SO$_4$)**. Outdoors in high humidity, acidic gases coalesce into superfine, suspended droplets, or aerosols, known as acid rain. A similar reaction occurs indoors, where acidic gases are deposited on surfaces and can cause damage.	*OUTDOOR SOURCES* **Natural sources** • Marine biological activity and active volcanoes • Atmospheric reactions of hydrogen sulfide: H$_2$S reacts rapidly with oxygen and forms both SO$_2$ and H$_2$SO$_4$ **Industrial processes** • The primary source of SO$_2$ is the combustion of sulfur-containing fossil fuels, including coal, gasoline, and diesel fuel • Industrial processes associated with pulp and paper production, cement industry, and petroleum refineries, especially when less-expensive, higher-sulfur-content fuels are used • Fireworks (can be localized, short-term risk) *INDOOR SOURCES* • Sulfur-containing fuels, such as kerosene and coal, used to cook and heat (relevant for historic houses as well as museums in areas that predominantly use these fuels) • Firewood used to cook and heat • Vulcanized rubber • Propane- or gasoline-powered machines, equipment, and generators	• Can be absorbed onto cellulosic materials, such as **paper**, including historic wallpaper, and **textiles**, where it catalytically hydrolyzes to H$_2$SO$_4$. H$_2$SO$_3$ and H$_2$SO$_4$ can also be absorbed directly onto these materials (the acid depolymerizes the cellulosic structure, and though damage is invisible, affected materials are embrittled and weakened) • SO$_2$ and related acids react with animal skins, such as **leather** and **parchment** [this breaks down the molecular structure and weakens the material; as a result, surface becomes powdery and is easily abraded (red rot)] • With its pollutant progeny, reacts with acid-sensitive **pigments**, resulting in typically nonreversible color change (e.g., lead white is converted to black lead sulfate, resulting in darkened color); lead-tin yellow, chrome yellow, verdigris, chrome orange, emerald green, and chrome red, among others, also are darkened by sulfates • Fades **dyestuffs**, affecting color of watercolors, textiles, costumes, etc. • Most **metals**, including copper, silver, bronze alloys, and aluminum, are susceptible to corrosion by any acidic species, causing irreversible damage • Silver salts in **photographs** are attacked, darkening the image • Attacks stone such as **limestone**, **marble**, **dolomite**, and other carbonate minerals or calcareous materials such as **shells**, **clays**, and **tiles**; at-risk objects include sculpture, natural history collections, and low-fire ceramics • When adsorbed on soot or carbon particles on dirty objects, can be oxidized to sulfuric acid or sulfurous acid, a risk for all **acid-sensitive** materials
Nitrogen oxides (NO$_x$) NO$_x$ is a collective term for **nitrogen monoxide (NO)** and **nitrogen dioxide (NO$_2$)**. Colorless NO is a primary vehicular pollutant. It reacts with other chemical species in the air to produce many other reactive nitrogen compounds, especially NO$_2$, a pungent red gas partly responsible for the color of photochemical smog. Oxidation (by ozone, UV irradiation, etc.) of nitrogen oxides generates **nitrous acid**, **HNO$_2$**, and **nitric acid**, **HNO$_3$**. This occurs indoors and outdoors. These acidic analogues are highly reactive.	*OUTDOOR SOURCES* **Natural sources** • Natural sources include lightning and biological processes such as soil microbes, vegetation, biomass fires, etc. • Agricultural fertilizers **Industrial processes** • Combustion of fossil fuels for industry and vehicles (high concentrations associated with urban traffic and thermal power plants) • Fireworks (temporary but relevant source) *INDOOR SOURCES* **Gas-phase reactions** • Formation of acids: reaction of NO and NO$_2$ on interior surfaces, including glass, and with carbon and carbonaceous aerosols generates HNO$_2$ and HNO$_3$, respectively **Indoor activities** • Stoves, heaters, fireplaces, and other sources of combustion • Tobacco smoke • Dry-process photocopiers • Degradation of cellulose nitrate objects **Construction materials/activities** • Generators and heavy equipment that use fuel-combustion engines	• Nitrous and nitric acids can damage the same **acid-sensitive materials** attacked by sulfuric or sulfurous acids • NO$_2$ enhances deterioration effects of SO$_2$ on **leather**, **metals**, **stone**, etc. • Corrosion of **copper-rich silver**. • Nitrogen pollutants fade **dyed fibers** in textiles, costumes, drapery, tapestries, etc. Reactions with **dyestuffs** alter color of textiles • Nitrogen pollutants fade certain **inks** as well as **organic pigments** in illuminated manuscripts, etc. • Nitrogen pollutants degrade **fibers** made from rayon, silk, wool, and nylon 6, causing yellowing and embrittlement • Nitrogen pollutants corrode **zinc**; synergistic effect with H$_2$S • Affects tarnishing of **copper** and **silver** by hydrogen sulfide
Reduced sulfur compounds **Hydrogen sulfide (H$_2$S)** **Carbonyl sulfide (COS)** **Carbon disulfide (CS$_2$)** **Hydrogen sulfide (H$_2$S)** smells like rotten eggs. It is responsible for the odor	*OUTDOOR SOURCES* **Natural sources** • Volcanoes, geothermal steam, geysers, sulfur wells, hot springs • Oceans, seas, marine areas • Marshes, soils, and wetlands • Biological activity, decomposition of organic material, release from vegetation, biomass burning, forest fires, tropical forests, etc.	• H$_2$S destroys immature **plant tissue** (relevant for natural history or botanical collections) • **Lead pigments: carbonates** (hydrocerussite or lead white) and **oxides** (e.g., red lead pigment) are susceptible to darkening by H$_2$S • **Metals: copper** metal exposed to H$_2$S develops a black copper sulfide layer, eventually replaced by a green patina of basic copper sulfate; extremely damaging to **silver** and its salts; tarnishes silver objects; reacts with silver salts in photographs; reacts with

Table 2 Major Gaseous Pollutants of Concern to Museums, Galleries, Archives, and Libraries: Sources and At-Risk Materials (*Continued*)

Gaseous Pollutants[a]	Major Sources and Some Important Minor Sources	At-Risk Materials
common to hot springs, as well as that noticed at wastewater treatment plants. Hydrogen sulfide is extremely toxic to people, but is detectable at very low concentrations (1 ppb). Collections are susceptible to reduced sulfur compounds at even lower levels (ppt).	**Industrial processes** • Fuel and coal combustion • Production of viscose rayon, vulcanization of rubber, etc. • Petroleum production, paper processing, and wood pulping **Atmospheric chemistry** • H_2S and COS can be formed by oxidation of carbonyl disulfide *INDOOR SOURCES* **Collections and objects** • Mineral specimens that contain pyrite (iron sulfide, FeS_2); sulfate-reducing bacteria in waterlogged objects **Display case materials** • Offgassing from sulfur-containing proteins in materials used in exhibition and display case design, especially silks, wools, and felts • Adhesives, especially those made from animal hide, such as rabbit skin glue **Construction materials/activities** • Arc welding (can be significant during renovation) **Flooring materials** • Wool carpets	silver inlays, silver gilt, etc.; reacts with **bronze**, **lead**; has synergistic effect with NO_2 to corrode **zinc** (see NO_2) • Low-fire **ceramics** • **Stone**, especially interior building stone • **Leather** (see sulfur dioxide)
	Strong Oxidizing Pollutants	
Ozone (O_3) is a major constituent of smog that directly affects people, plants, and property. **Peroxyacetyl Nitrate (PAN)** (**CH_3-COO-O-NO_2**) is a principal secondary pollutant in photochemical smog **Peroxides (—O:O—)**, the simplest of which is hydrogen peroxide (HO:OH), are extremely reactive because of the oxygen-oxygen bond. Strong oxidizing pollutants present a great risk to collections. Oxidants break down the structure of organic materials by attacking carbon-carbon double bonds. Oxidants can also react with other gaseous pollutants, such as NO_x, to create acidic analogs; radicals such as the hydroxyl radical, •OH; and other destructive reaction by-products [e.g., oxidation of aldehydes into acetic acid (see organic carbonyl pollutants entry)].	**Ozone-Specific Sources** *OUTDOOR SOURCES* • Smog: tropospheric (ground-level) ozone is a major secondary pollutant of vehicular and industrial emissions *INDOOR SOURCES* • Office/building equipment, including dry-process photocopiers and other office equipment • Electrical arcing, including electrostatic air cleaners or filter systems and electronic insect killers **PAN-Specific Sources** *OUTDOOR SOURCES* • Secondary pollutants from urban traffic emissions produced by gas-phase reactions between hydrocarbons and nitrogen oxide compounds, and reactions between organic carbonyl pollutants and hydroxy radicals (•OH) • Pollutants from ethanol-fueled vehicles • Forest fires **Peroxide-Specific Sources** *OUTDOOR SOURCES* • Secondary pollutant generated by nitrogen oxide chemical reactions with hydrocarbons, VOCs, and organic carbonyl pollutants. • By-product of atmospheric reactions of pollutants from gasohol fuels *INDOOR SOURCES* • Emission from deterioration of organic materials (e.g., rubber floor tiles) • Oil-based paints • Microorganism activities	• Artists' colorants: fading of **dyes** and **pigments** • Oxidation of organic compounds with double bonds (e.g., embrittles and cracks **rubber**) • **Electrical wire coatings** (of concern to industrial collections) • **Plants** (of concern to botanical and natural history collections) • Embrittles **fabrics**, **textiles**, and **cellulosic materials** • Enhances tarnishing of **silver** by reduced sulfur compounds • Causes discoloration of **photographic prints** • Attacks **paint binders** • Affects **leather**, **parchment**, and **animal skins** (of concern to natural history collections) • Adsorbed onto **building products** (plasterboards, painted walls, carpet, linoleum, pinewood, and melamine-covered particleboard), where it can react with and damage surfaces or be re-released into environment

Table 2 Major Gaseous Pollutants of Concern to Museums, Galleries, Archives, and Libraries: Sources and At-Risk Materials (*Continued*)

Gaseous Pollutants[a]	Major Sources and Some Important Minor Sources	At-Risk Materials
	Organic Carbonyl Pollutants: Aldehydes and Organic Acids	
Organic carbonyl pollutants **Aldehydes** • **Formaldehyde (HCHO)** • **Acetaldehyde (CH₃CHO)** **Organic acids** • **Formic acid (HCOOH)** • **Acetic acid (CH₃COOH)** Most materials damage by organic carbonyl pollutants is attributed to acetic acid or to formaldehyde. It is suspected that damage credited to formaldehyde is really due to its oxidized form, formic acid. Correspondingly, oxidation of acetaldehyde generates acetic acid. However, the risk from direct emissions of acetic acid is greater. (See also specific entries for organic acids, aldehydes, and formaldehyde.)	*OUTDOOR SOURCES* **Atmospheric chemistry** • Secondary pollutants resulting from atmospheric reactions with industrial and vehicle pollutants • Precipitation: gases concentrate in fog, rain, and snow **Natural sources** • Biogenic emissions from vegetation • Biomass burning, forest fires, rainforest slash and burn, etc. • Biodeterioration of organic materials *INDOOR SOURCES* **Gas-phase reactions** • Indoor reactions of outdoor pollutants that infiltrate buildings • Evaporation from hot water (e.g., dishwashers, showers) • Construction and building materials, especially materials used in the construction of display cases and storage cabinets; laminated materials • Coatings, sealants, paints and adhesives, some polyvinyl acetate adhesives, oil-based paints • New houses (in older houses off-gassing has decreased significantly or ceased): materials used in cabinet making, doors and plywood subfloors as well as floor assemblies • Materials manufactured with urea formaldehyde, including foam insulation; other formaldehyde-based resins such as phenol formaldehyde wood products • Wood and wood products • Wood-based panel products, especially with urea formaldehyde and melamine formaldehyde binding resins (e.g., pressed wood, composite wood panels, chipboard, particleboard, medium-density fiberboard, parquet) • Other wood-based building materials **Flooring materials** • Cork products • Flooring, linoleum, carpets **Other materials** • Furniture and furniture coatings, varnishes • Consumer and household products, such as hair spray, perfumes and cosmetics, air fresheners, cleaning agents, etc. • Paper and paper products • Finished fabrics (See also sources specific to formic acid and acetic acid, aldehydes, and formaldehyde.)	• **Metal** corrosion: non-noble metals such as **leaded**-bronzes, **copper alloys**; base metals such as **lead**, **copper**, **silver**; corrosion of **cabinetry hardware** coated with cadmium, lead, magnesium, and zinc • Acid hydrolysis of **cellulose** reduces degree of polymerization, which is discernible as embrittlement • Attacks **calcareous materials**: land shells and seashells (i.e., Byne's disease), corals, limestone, calcium-rich fossils • Low-fire **ceramics** • Reacts with **enamel** and **glass**, especially previously damaged and weakened glass, such as weeping glass • Stained glass: corrodes **lead joins** between glass panes

Organic acids
  Acetic acid (CH₃COOH)
  Formic acid (HCOOH)
 	
(See also organic carbonyl pollutants.)
	OUTDOOR SOURCES
	• Textile industry effluents and emissions
	
	INDOOR SOURCES
	• Formaldehyde-free wood composite boards
	Formic-Acid-Specific Sources
	• Oxidation product from reaction of formaldehyde with light
	Acetic-Acid-Specific Sources
	• Degradation of cellulose acetate objects
	• Silicone sealants
		(See at-risk materials under organic carbonyl pollutants.)

Table 2 Major Gaseous Pollutants of Concern to Museums, Galleries, Archives, and Libraries: Sources and At-Risk Materials (*Continued*)

Gaseous Pollutants[a]	Major Sources and Some Important Minor Sources	At-Risk Materials

Aldehydes
  Formaldehyde (HCHO)
  Acetaldehyde (CH_3CHO)
 	
(See also organic carbonyl pollutants and formaldehyde.)
	OUTDOOR SOURCES
	Industrial processes
	• Primary pollutant from vehicles using alcohol fuels (e.g., methanol, gasohol) and ethanol/gasoline fuel blends
	• Automobile manufacturing, especially painting
	
	INDOOR SOURCES
	• Combustion by-products, cooking, heating, and tobacco smoke
	• Artists' linseed oil paints, other drying oils
	
	Construction and building materials
	• Terra cotta bricks
	• Ceramic manufacturing, kiln exposures
	• Vinyl, laminates, wallpapers, acrylic-melamine coatings
	• Alkyd paints
	• Latex and low-VOC latex paints
	• Secondary pollutants produced by reaction of ozone and some carpet materials
		(See at-risk materials under organic carbonyl pollutants.)

Formaldehyde Formaldehyde is easily oxidized to formic acid, which is most likely the aggressive chemical.	*INDOOR SOURCES* • Natural history wet specimen collections • Consumer products, including decorative laminates, fiberglass products • Dry-process photocopiers • Textiles such as new clothes and fabrics, dry-cleaned clothes, permanent press fabrics, drapery, clothing, carpets, wall hangings, furniture coverings, unfinished fabrics, dyeing process residues, chemical finishes, etc. • Fungicide in emulsion paints and glues (e.g., wheat pastes) • PVC-backed carpeting • Floor finishes	• **Silver** tarnish or surface discoloration • Reacts with unexposed **photographic films** and **photographs**, especially black & white • Cross-links **proteins** (e.g., collagen), resulting in loss of strength in animal hides, leather objects, parchments, etc. (also attacks objects with gelatin, animal glue, or casein binders) • Reacts with **textiles**, **fibers** • Attacks buffered **papers** and reacts with metallic-salt inclusion in paper • Discoloration of **dyes**, fading of **organic colorants** • Chemically changes **inorganic pigments**: insoluble basic copper carbonate (main component of azurite) is converted to soluble copper acetate (See also at-risk materials in organic carbonyl pollutants.)
	Other Potentially Damaging Pollutants	
Ammonia (NH_3) **Ammonium ion ($+NH_4$)** Most damage to museum collections is from the ammonium ion, produced when water and ammonia react.	*OUTDOOR SOURCES* **Natural sources** • Agriculture, especially fertilization, and animal wastes (animals are the largest global source of ammonia) • Biodeterioration (e.g., landfill gases), underground bacterial activity. **Industrial processes** • Fertilizer production *INDOOR SOURCES* • Household cleaning products • Museum visitors • Emulsion adhesives and paints • Alkaline silicone sealants • Concrete	• Blemishes **ebonite**, **natural resins** • Reacts with materials made from **cellulose nitrate**, forming ammonium salts that corrode **copper**, **nickel**, **silver**, and **zinc**

Table 2   Major Gaseous Pollutants of Concern to Museums, Galleries, Archives, and Libraries: Sources and At-Risk Materials (*Continued*)

Gaseous Pollutants[a]	Major Sources and Some Important Minor Sources	At-Risk Materials
Amines (R-NH$_2$) These alkali pollutants are derivatives of ammonia.	*INDOOR SOURCES* • Amine-based corrosion inhibitors [diethylaminoethanol (DEAE), cyclohexylamine (CHA), and octadecylamine (ODA)] used in humidification systems and ventilation ducts • Atmospheric reactions of nitrogen species and alkali pollutants released from new concrete • Epoxy adhesives	• Causes blemishes on **paintings**, usually when pollutant is dispersed through the ventilation system • Corrosion of **bronze**, **copper**, and **silver** • Darkens **linseed** oil and forms copper amine complexes with **copper pigments** (e.g., malachite) • Blemishes furniture **varnishes**
Fatty acids	*OUTDOOR SOURCES* • Vehicle exhaust *INDOOR SOURCES* • Animal skins, furs, taxidermy specimens, and insect collections (relevant for natural history collections and parchment) • Museum visitors • Combustion: burning candles, cooking • Adhesives • Linoleum	• Yellows **paper** and **photographic** documents • Corrodes **bronze**, **cadmium**, and **lead** • Blemishes **paintings**
Hydrochloric acid (HCl)	*OUTDOOR SOURCES* • Coal combustion • Oceans, sea mist spray	• HCl is an acidic gas; hence, it attacks **acid-sensitive materials**, especially under high-humidity conditions often present in coastal regions • Increases corrosion rate of metals • Affects tarnishing of **copper** and **silver** by hydrogen sulfide
Water vapor (H$_2$O) Water vapor (i.e., relative humidity) is a critical parameter for museum collections. Besides direct affects of humidity changes on collections, water vapor increases corrosion and decay rates, and is involved in most chemical reactions.	*OUTDOOR SOURCES* • Atmosphere (high-humidity days) • Bodies of water *INDOOR SOURCES* • Fountains • Humidifiers • People • Wet cleaning activities	• Increases hydrolysis reactions on **organic objects**, which usually leads to damage (e.g., hydrolysis of cellulose weakens paper objects) • Increases effect of nitrogen oxides on photographs • Increases hydrogen sulfide corrosion of **copper** and **silver** • Controlling factor in **bronze disease** • Increases deterioration of materials (e.g., **metal** corrosion, efflorescence of calcareous objects, and photo-oxidation of **artists' colorants**) • Increases fading of **dyestuffs** used in textiles and watercolors
Particles (fine and coarse)[b]	• *General*: atomizing humidifier; burning candles; cooking; laser printers; renovation; spray cans; shedding from clothing, carpets, packing crates, etc. (from abrasion, vibration, or wear); industrial activities; outdoor building construction; soil • *Biological and organic compounds*: microorganisms, degradation of materials and objects, visitors and animal danders, construction activities • *Soot (organic carbon)*: burning candles, incense, fires, coal combustion, vehicle exhaust • *Ammonium salts (ammonium sulfate)*: reaction of ammonia with SO$_2$ or NO$_2$ inside or outside or on solid surfaces	• *General*: abrasion of surfaces (critical for magnetic media); disfiguration of objects [especially critical for surfaces with interstices that entrap dust (e.g., with pores, cracks, or micro irregularities)]; may initiate or increase corrosion processes; may initiate catalysis forming reactive gases • *Soot*: disfiguration of porous surfaces (painting, frescoes, statues, books, textiles, etc.), increases rate of metals corrosion

[a]Source for gaseous pollutants section: Grzywacz (2006).
[b]Source for particle section: Tétreault (2003).

risk. Hydrocarbons and other volatile organic compounds (VOCs), such as alcohols and ketones, may be important for other considerations such as human health and comfort, but generally are not threats to artifacts. Outdoor sources of airborne pollutants are primarily industrial and human activities. Inorganic outdoor pollutants that cause material damage are important, but as the use of alcohol-based fuels increases, organic species, especially formaldehyde and organic acids (Anderson et al. 1996; Schifter et al. 2000), become relatively more important. Geological and biological activities release hydrogen sulfide and ammonia; the agricultural industry is also a major ammonia source (Allegrini et al. 1984; Walker et al. 2000). Inside buildings, construction materials emit organic carbonyls such as carboxylic acids and aldehydes (Gibson et al. 1997; Grzywacz and Tennent 1994, 1997; Meininghaus et al. 2000).

Materials Damage Caused by Airborne Pollutants

Pollutant-monitoring surveys of collections and laboratory studies have provided important data on the effect of airborne pollutants on materials (Table 2). Damage to materials is the sum of many parameters in the immediate environment. High levels of a single pollutant may cause serious damage even when all other conditions are ideal. However, when many pollutants act together and temperature, relative humidity, and light intensity are elevated, deterioration processes are almost always accelerated. The prior history of treatment, storage, or excavation may also aggravate chemical reactions. Tétreault's (1994, 2003) summary of materials damaged by pollutants can help determine which materials require special care. Brokerhof (1998), Craft et al. (1996), Grzywacz (1999, 2006), Hatchfield (2002), Lavédrine (2003), Ryhl-Svendsen (1999), and Tétreault (1994, 1999, 2003) summarized airborne pollution control strategies for rooms and enclosures.

Damage to artifacts is cumulative and irreversible. All efforts to minimize exposing collections to pollutants are beneficial. Both long-term exposure to low levels of pollutants and short-term exposure to high pollutant concentrations can damage susceptible objects. Not all damage is immediately visible, especially with organic materials (e.g., papers, textiles, animal skins), because damage is loss of strength, brittleness, etc. (Bogaty et al. 1952; Dupont and Tétreault 2000; Graedel and McGill 1986; Oddy and Bradley 1989; Tétreault et al. 1998). Note that concentrations of gaseous pollutants are reported in volumetric units: parts per million (ppm) or parts per billion (ppb), which are temperature and pressure dependent. To standardize reporting, the Compressed Air and Gas Institute (CAGI 2002) recommends using a standard temperature and pressure of 68°F and 14.7 psi. Concentrations of particulate pollutants are reported in gravimetric units [e.g., micrograms per cubic metre ($\mu g/m^3$)], which is temperature and pressure independent.

Autocatalytic degradation of film is a problem. Most cellulose nitrate film stock eventually becomes so unstable that fire and explosion are high risks. Frozen storage is the only option from a human health and safety perspective. Cellulose nitrate sculpture likewise degrades rapidly (Derrick et al. 1991). Degradation products may include nitric acid, when catalyzed by small amounts of sulfate esters remaining from manufacture, or nitrogen dioxide, in the case of uncatalyzed thermal or photochemical decomposition (Selwitz 1988).

Cellulose acetate film stock ("safety film") is also chemically unstable, but does not pose the fire or explosive hazard inherent in cellulose nitrate films. Over time, it deteriorates autocatalytically and liberates free acetic acid ("vinegar syndrome"). The amount of acetic acid liberated can be many orders of magnitude greater than any other single source in museums and archives. As such, it is a risk not only to the film itself, but also to all other acid-sensitive materials. Consequently, these films must be properly contained.

Organic carbonyl pollutants such as formaldehyde, acetic acid, and formic acid are the most damaging to collections (Brimblecombe et al. 1992; Gibson 1999; Grzywacz 2003; Grzywacz and Tennent 1994, 1997; Hatchfield 2002; Hatchfield and Carpenter

1986; Hopwood 1979; Tétreault 2003). Organic carbonyl pollutants are a risk at a few parts per billion by volume in air, and can damage calcareous materials such as limestone, land and sea shells, metal alloys, low-fired ceramics, and, less obviously, organic materials (see Table 2). Reduced-sulfide compounds such as hydrogen sulfide (H_2S) and carbonyl sulfide (COS) are significant threats at much lower concentrations, at a few parts per trillion (Brimblecombe et al. 1992; Watts 1999; Watts and Libedinsky 2000). Fortunately, sources of H_2S and COS are less prevalent than sources of organic carbonyl pollutants.

Another major source of damage is surface particle deposition. Large particles (PM10, ≥10 μm) entering the building through air intakes are usually removed effectively by coarse particle filters. However, people (including museum visitors) are a significant source of large particles from skin cell shedding, particles tracked in on shoes, clothing, and the air surrounding them as they pass through exterior doors (Yoon and Brimblecombe 2001). People-borne particles are not usually removed by HVAC filters. Large particles settle predominantly on horizontal surfaces; they can also soil vertical surfaces near the floor and extending up to eye level. Yoon and Brimblecombe (2001) identified a relation between the proximity of visitors to objects and soiling. The main risks posed by large particles are aesthetic degradation, caused by a loss of gloss, and scratched surfaces, caused by hard soil dusts during cleaning.

Fine particles (PM2.5) are not removed well by many coarse particle filters. Soot is the most important particle type in this size range. It does not settle out of the air easily and is influenced by energetic air molecules, natural and forced convection, and turbulent air flows. Small particles collect on all surfaces (vertical, horizontal, downward-facing, or upward-facing). Black soot particles can be a major soiling risk on large, unprotected surfaces such as tapestries or on small, porous, soft natural history collections and book margins.

Ligocki et al. (1990, 1993), Nazaroff and Cass (1991), Nazaroff et al. (1990, 1992, 1993), and Salmon et al. (2005) examined the origin, fate, and concentration of particles in several museums in southern California. Rates of particle deposition were established for a typical historical house and several museums with standard air-conditioning filtration. From the deposition rate, "time for perceptible soiling" was established, to characterize the building by when soiling could be expected to be barely visible to a normal observer. Bellan et al. (2000) showed that the amount of coverage by small black particles, similar to soot, on a white surface was just detectable at a surface coverage of 2.6%, if the observer could compare a sharp edge of soiled surface against a nonsoiled surface. This value is 12 times larger than published in earlier literature (Hancock et al. 1976). Druzik and Cass (2000) determined that, if the museums studied by Nazaroff et al. (1990) are typical of most medium-sized art museums with HVAC systems, the time to onset of perceptible soiling of vertical surfaces is 24 to 86 years.

Some forms of chemical deterioration have been traced to particle deposition. Toishi and Kenjo (1975) extensively covered the risk from new concrete. However, little is known about direct chemical degradation of historic materials by these particles. It has been speculated that particle deposition may accelerate cellulose degradation and metal corrosion, based on known reaction pathways of suspended particles and other materials-science investigations, such as the corrosion of copper alloys by soluble nitrates (Hermance et al. 1971).

"Realistic" Versus "Technically Feasible" Target Specifications. Responses to environmental factors vary, and often do not appear until the materials have significantly aged. Individual objects can also react differently than their nearest relatives in a class of objects. Providing the best available technology for a reasonably large collection to guard against all contingencies is not realistic. For most objects, it is feasible to create a safe and protective environment at a reasonable cost to the client such that they can be maintained indefinitely. Expanding protection beyond certain limits for

smaller artifacts and smaller collections becomes less practical at the whole-building mechanical control level. For artifacts with specific problems or risks, it is usually better to provide microenvironments.

"Best available technology" often implies protection on a diminishing cost/benefit scale. Museums, libraries, and archives are frequently nonprofit organizations on tight budgets. Insisting on extraordinary humidity control or filtering out every air pollutant that is theoretically damaging can endanger long-term viability of the effort. Insistence on best available technology may also have the unintentional effect of highlighting the lack of useful engineering solutions rather than the more important role of HVAC systems as efficient, protective, and necessary.

Risk Management Plans for Collections. Preservation of collections is a tradeoff among many factors. There is not one golden rule; instead, risk management approaches are used (Ashley-Smith 1999; Brimblecombe 2000; Dahlin et al. 1997; Hens 1993; Michalski 1996b; Stock and Venso 1993; Tétreault 2003; Thickett et al. 1998; Waller 1999). Waller and Michalski (2005) report on a preventive conservation software tool to determine appropriate set points and ranges for temperature and relative humidity.

DESIGN PARAMETERS

PERFORMANCE TARGET SPECIFICATIONS

Temperature and Relative Humidity

No two collections are identical. Ideally, temperature and humidity targets and tolerances for each facility are developed collaboratively by a conservator with expert knowledge of the damage factors and realities of the collection, and a design engineer with extensive experience in designing systems that meet the needs of many different types of collections. That approach ensures specifications most likely to provide maximum life for the collection. Experienced experts are best equipped to identify areas of special risk and devise solutions, and to properly manage economic and other tradeoffs, although this level of expertise is not always available.

Table 3 summarizes the probable effects of various specification options, based on the best current knowledge (including all available data, research results, and judgment of conservators). Michalski (1991, 1993, 1995, 1996a, 1996b, 1999) reduced permissible fluctuations to five classes: AA, A, B, C, and D. Gradients are conservatively considered to add to short-term fluctuations because artifacts can be moved from one part of a space to another, adding a space-gradient fluctuation to the dynamic fluctuations of the HVAC.

Class AA control has the highest potential for energy consumption and affords no protection to historic buildings in cold climates. Older buildings are at most risk to damage from condensation on windows, walls, and roofs. Therefore, HVAC application in historic buildings must consider the risk to the structure and building envelope. Mecklenburg et al. (2004) discuss the concept of preserving both the collections and the buildings. Class A control has the benefit of some reduction of energy consumption and, with seasonal lowering of the relative humidity set point in the winter, affords some protection to historic buildings in cold climates. Older buildings at these lower temperature and relative humidity specifications are at less risk to damage from condensation on windows, walls, and roofs.

Class A is the optimum for most museums and galleries. Two possibilities with equivalent risks are given: a larger gradient and short-term fluctuations, or a larger seasonal swing. Stress relaxation is used to equate ±10% rh seasonal swing to a short ±5% rh. A major institution with the mandate and resources to prevent even tiny risks might move toward the narrower fluctuations of Class AA. However, design for very-long-term reliability must take precedence over narrow fluctuations.

Classes B and C are useful and feasible for many medium and small institutions, and are the best that can be done in most historic

buildings. Class D recognizes that control of dampness is the only climatic issue.

Architectural Considerations. Building envelopes play an important role in controlling moisture migration into the space. Architectural design should include heavy insulation, and consider possible vapor barriers. Control of openings, window materials, and floor slab insulation are critical in the design. Rainwater runoff design should be considered in the HVAC relationship to collection storage and display areas.

Building Envelope Issues

Persily (1999) discusses building envelopes. Museums, libraries, and archives often ask mechanical engineers for "improved climate control" in buildings never designed for such purposes. Conrad (1995) grouped such buildings (and building parts) by their possibilities and limitations into seven categories. In an abridged version of his scheme, Table 4 lists the possible classes of fluctuation control possible each class of building. Local climate determines which possibility is most likely. For detailed guidance on air leakage and thermal and moisture performance of building envelopes, refer to Chapters 23, 24, and 30 of the 2005 *ASHRAE Handbook—Fundamentals*.

Airborne Pollutant Targets

Assigning target concentrations for airborne pollutants is a complex task. An object's susceptibility depends on a variety of factors (including historical storage and conservation treatments, and current stability), and is linked to other environmental factors, such as temperature, relative humidity, and light levels (Gibson 1999). The conservator, collection manager, or curator considers all these factors and more.

Principal airborne pollutants for museums, galleries, archives, and libraries are listed in Table 5. Nitrogen oxides, fine particles, ozone, and sulfur dioxide are generated mainly outside. Hydrogen sulfide can be generated inside the building [depending on materials (especially carpets and wall coverings), number of visitors, and inside activities] or infiltrate the building envelope (depending on geographic location and factors such as biomass decay, volcanoes, sulfur springs, etc.). Wood, construction materials, indoor activities, and artifacts mainly generate organic acids and aldehydes (see Table 2), which can be found at high levels in enclosures. Total VOCs are included; they can be used as a metric for the overall air quality in the area. Table 5 presents suggested concentration limits, action limits, air quality recommendations, natural background and urban concentrations, acute human toxicity levels, U.S. Environmental Protection Agency (EPA) Clean Air Act Limits, and World Health Organization time-weighted average (TWA) limits. Limits in the first four columns are based on Tétreault's (2003) **lowest observable adverse effect dose (LOAED)** and **no observable adverse effect level (NOAEL)**, which combine critical review of detailed in situ observations with laboratory studies and provide substantial quantitative information on adverse effects of pollutants on materials. Extensive sets of LOAED and NOAEL are available in Tétreault (2003).

It is preferable to exclude pollutant sources by properly selecting construction and cleaning products used inside (e.g., not using vinegar-based cleaning products or amine compounds as corrosion inhibitors in humidification systems; see Table 2).

Controlling relative humidity below 60 or 45% for long-term preservation and maintaining temperature at about 65°F can minimize deterioration of collections from airborne pollutants. Cleanliness of the collection is also important, because salts, fatty acids, or metallic dirt may initiate or accelerate some deterioration caused by gaseous pollutants.

For long-term preservation, levels of airborne pollutants should be below 1 ppb for gases and less than 1 $\mu g/m^3$ for fine particles. Low levels of airborne pollutants can be achieved in many ways,

Table 3 Temperature and Relative Humidity Specifications for Collections

Type	Set Point or Annual Average	Class of Control	Maximum Fluctuations and Gradients in Controlled Spaces		Collection Risks and Benefits
			Short Fluctuations plus Space Gradients	Seasonal Adjustments in System Set Point	
General Museums, Art Galleries, Libraries, and Archives All reading and retrieval rooms, rooms for storing chemically stable collections, especially if mechanically medium to high vulnerability.	50% rh (or historic annual average for permanent collections) Temperature set between 59 and 77°F *Note*: Rooms intended for loan exhibitions must handle set point specified in loan agreement, typically 50% rh, 70°F, but sometimes 55% or 60% rh.	**AA** Precision control, no seasonal changes	±5% rh, ±4°F	Relative humidity no change Up 9°F; down 9°F	No risk of mechanical damage to most artifacts and paintings. Some metals and minerals may degrade if 50% rh exceeds a critical relative humidity. Chemically unstable objects unusable within decades.
		A Precision control, some gradients or seasonal changes, not both	±5% rh, ±4°F	Up 10% rh, down 10% rh Up 9°F; down 18°F	Small risk of mechanical damage to high-vulnerability artifacts; no mechanical risk to most artifacts, paintings, photographs, and books. Chemically unstable objects unusable within decades.
			±10% rh, ±4°F	RH no change Up 9°F; down 18°F	
		B Precision control, some gradients plus winter temperature setback	±10% rh, ±9°F	Up 10%, down 10% rh Up 18°F, but not above 86°F	Moderate risk of mechanical damage to high-vulnerability artifacts; tiny risk to most paintings, most photographs, some artifacts, some books; no risk to many artifacts and most books. Chemically unstable objects unusable within decades, less if routinely at 86°F, but cold winter periods double life.
		C Prevent all high-risk extremes	Within 25 to 75% rh year-round Temperature rarely over 86°F, usually below 77°F		High risk of mechanical damage to high-vulnerability artifacts; moderate risk to most paintings, most photographs, some artifacts, some books; tiny risk to many artifacts and most books. Chemically unstable objects unusable within decades, less if routinely at 86°F, but cold winter periods double life.
		D Prevent dampness	Reliably below 75% rh		High risk of sudden or cumulative mechanical damage to most artifacts and paintings because of low-humidity fracture; but avoids high-humidity delamination and deformations, especially in veneers, paintings, paper, and photographs. Mold growth and rapid corrosion avoided. Chemically unstable objects unusable within decades, less if routinely at 86°F, but cold winter periods double life.
Archives, Libraries Storing chemically unstable collections	Cold Store: −4°F, 40% rh	±10% rh, ±4°F			Chemically unstable objects usable for millennia. Relative humidity fluctuations under one month do not affect most properly packaged records at these temperatures (time out of storage becomes lifetime determinant).
	Cool Store: 50°F 30 to 50% rh	(Even if achieved only during winter setback, this is a net advantage to such collections, as long as damp is not incurred)			Chemically unstable objects usable for a century or more. Such books and papers tend to have low mechanical vulnerability to fluctuations.
Special Metal Collections	Dry room: 0 to 30% rh	Relative humidity not to exceed some critical value, typically 30% rh			

Note: Short fluctuations means any fluctuation less than the seasonal adjustment. However, as noted in the section on Response Times of Artifacts, some fluctuations are too short to affect some artifacts or enclosed artifacts.

including building design, filtration, maintenance, and operations. If the HVAC system cannot provide the specified protection from contaminants, it may be necessary to place collections in appropriate microclimates.

A building is a complex, dynamic environment that affects the indoor concentration and fate of airborne pollutants. Detailed discussion is beyond the scope of this chapter, but major factors influencing airborne pollutants include the following:

• Outdoor pollutant load
• Visitor traffic and indoor activities
• Location of outside air intake
• Location and type of air delivery vents in collection spaces
• Ratio of outside to recirculated air when the building is open to the public and staff, and when it is closed to the public

• Particle and gaseous filter efficiency and filter maintenance
• Location and fit of filters in HVAC system
• Janitorial, building, and grounds maintenance practices

The surface temperature of walls and artifacts can influence particle deposition. For these reasons, the HVAC engineer has considerable flexibility in controlling filtration, although some architectural, maintenance, and geographic factors are beyond control. Nevertheless, engineers should be aware of these issues and bring them into design discussion when appropriate.

Many institutions with a small or limited operating budget may prefer to use enclosures. Long-term preservation of collections in either rooms or enclosures must be discussed between the client, design engineers, and conservation professionals. In addition to decision factors already stated, ethical aspects of the exhibition,

Table 4   Classification of Climate Control Potential in Buildings

Category of Control	Build-ing Class	Typical Building Construction	Typical Type of Building	Typical Building Use	System Used	Practical Limit of Climate Control	Class of Control Possible
Uncontrolled	I	Open structure	Privy, stocks, bridge, sawmill, well	No occupancy, open to viewers all year.	No system.	None	D (if benign climate)
	II	Sheathed post and beam	Cabins, barns, sheds, silos, icehouse	No occupancy. Special event access.	Exhaust fans, open windows, supply fans, attic venting. No heat.	Ventilation	C (if benign climate) D (unless damp climate)
Partial control	III	Uninsulated masonry, framed and sided walls, single-glazed windows	Boat, train, lighthouse, rough frame house, forge	Summer tour use. Closed to public in winter. No occupancy.	Low-level heat, summer exhaust ventilation, humidistatic heating for winter control.	Heating, ventilating	C (if benign climate) D (unless hot, damp climate)
	IV	Heavy masonry or composite walls with plaster. Tight construction; storm windows	Finished house, church, meeting house, store, inn, some office buildings	Staff in isolated rooms, gift shop. Walk-through visitors only. Limited occupancy. No winter use.	Ducted low-level heat. Summer cooling, on/off control, DX cooling, some humidification. Reheat capability.	Basic HVAC	B (if benign climate) C (if mild winter) D
Climate controlled	V	Insulated structures, double glazing, vapor retardant, double doors	Purpose-built museums, research libraries, galleries, exhibits, storage rooms	Education groups. Good open public facility. Unlimited occupancy.	Ducted heat, cooling, reheat, and humidification with control dead band.	Climate control, often with seasonal drift	AA (if mild winters) A B
	VI	Metal wall construction, interior rooms with sealed walls and controlled occupancy	Vaults, storage rooms, cases	No occupancy. Access by appointment.	Special heating, cooling, and humidity control with precision constant stability control.	Special constant environments	AA A Cool Cold Dry

Source: Adapted from Conrad (1995).

security, overall long-term preservation goals, object/pollutant interactions, and IAQ performances of the HVAC system and enclosures should taken in consideration.

SYSTEM SELECTION AND DESIGN

A typical project consists of many different types of spaces, such as galleries, reading rooms, search rooms, laboratories, conference rooms, stacks, storage rooms, restaurants or cafeterias, auditoriums, rare book vaults, offices, lounges, and study rooms. Areas housing objects or collections are considered to need a special environment, defined by the criteria in the previous section, for preventive conservation or preservation.

The HVAC system for a preservation environment must maintain relative humidity, maintain temperature and air movement, and filter air, evenly throughout the space, with minimum risk of damage to collections, at a cost the institution can support. Special HVAC system indications usually fall into two general categories: museums, including galleries and other spaces where environmentally sensitive objects are kept or displayed, and libraries, including archives and other spaces where primarily paper-based collections are stored and used, with some additional concern for film and other media.

One primary requirement is high performance with low or limited annual operating budgets. This shifts focus to capital investments in systems and features to minimize operating costs and problems.

Design Issues

Functional Organization. Maintaining an effective preservation environment depends heavily on HVAC systems, but other factors, such as basic architectural design (e.g., windows, vapor retardants) and building operation (e.g., hours of operation, availability of tempering sources), must complement HVAC design. Ideally, the HVAC engineer should be involved early in project planning to ensure that space layout does not present unnecessary problems. In the best case, collections are housed separately from visitors, users, staff, and all other functions. Where this is not possible, processes and activities that threaten collections should be physically and mechanically separated from the collections. Separate systems for collection and noncollection areas allow isolation of environments and can reduce project costs for noncollection areas.

A typical issue, particularly in fine art museums, is whether to treat executive offices as collection spaces. This should be considered carefully, not only for the added capital and operating cost, but also for the risks to the collection if offices are not so treated and are nonetheless used for collections display.

Frequently used entrances, such as the lobby and loading dock, are some of the most environmentally disruptive elements. The engineer should ensure that loads from these spaces are managed and isolated from primary collection areas.

Substantial holdings of film ideally should be housed separately from other collections; for details, see the section on Materials Damage Caused by Airborne Pollutants.

Humidity-Tolerant Building Envelope. Winter humidification should be a high priority in a heated building in temperate or cold climates, but the humidity tolerance of the building must be considered. Often, the building envelope has problem condensation (on single-glazed windows, on window frames, or in the exterior wall or roof) in winter at interior humidities as low as 25%. This condensation can cause cosmetic or substantive damage to the building. In such cases there are three alternatives: (1) keeping winter humidity stable and below the point where problem condensation occurs, (2) retrofitting the building envelope to tolerate higher humidity, or (3) reducing the space temperature.

Depending on the humidity level that can be maintained without problems, a collection may require that the envelope be modified to support higher winter humidity. These changes benefit collections, but present considerable design challenges and expenses. If a

Table 5 Current Recommended Target Levels for Key Gaseous Pollutants[a]
(in ppb, unless otherwise indicated)

Major Outdoor Pollutants in Museums	Suggested Pollutant Limits for Collections[b, c]		Action Limits[d]		Air Quality Recommendations		Reference Concentrations				
	Sensitive Materials[e]	General Collections	High	Extremely High	Archival Document Storage	Libraries, Archives, and Museums	Natural Background Levels	Urban Areas	Health: Acute Toxicity Level for 1 h Exposure[f]	EPA Clean Air Act Limits[g]	World Health Organization[h] TWA Limits
Nitrogen dioxide, NO_2	<0.05 to 2.6	2 to 10	26 to 104	>260	Canada: 2.6 USA: 2.6	2.6	0.05 to 4.9	1.6 to 68 USA: 22 to 52 Canada: 16 to 22 Europe: 2 to 34	244 OSHA: 5 ppm[i]	50 (1 y)	104 (1 h) 21 (annual) 62 (8 h)
Nitrogen monoxide,[j] NO, see ozone							0.16 to 1.6	1 to 32	OSHA: 25 ppm		
Acidic nitrogen gases, HNO_2, HNO_3	<0.1	<1.0					0.02 to 0.2	1 to 49			
Ozone, O_3	<0.05	0.5 to 5	25 to 60	75 to 250	Canada: 1.0 USA: 13	2.0	1 to 100	5 to 200 USA: 100 to 120 Canada: 17 to 21 Europe: 65 to 145	90 OSHA: 100	120 (1 h) 80	60 (8 h)
Sulfur dioxide, SO_2	<0.04 to 0.4	0.4 to 2	8 to 15	15 to 57	Canada: 0.4 USA: 0.4	1.0	0.04 to 11 Rural USA: 6 to 10 Europe: 1 to 14	2 to 380 USA: 4 to 6 Canada: 4 to 6 Europe: 2 to 94	251 OSHA: 5 ppm	30 (1 y) 140 (24 h)	190 (10 min) 10 (24 h) 19 (annual)

Major Indoor-Generated Pollutants in Museums	Suggested Pollutant Limits		Action Limits			Reference Concentrations				
	Sensitive Materials	General Collections	High	Extremely High		Natural Background Levels	Urban Areas	Health: Acute Toxicity Level for 1 h Exposure	EPA Clean Air Act Limits	World Health Organization TWA Limits
Hydrogen sulfide, H_2S	<0.010	<0.100	0.4 to 1.4	2.0 to 20		0.005 to 10	0.1 to 5	30 ppm OSHA: 10 ppm		107

Organic Carbonyl Pollutants

		Suggested Pollutant Limits		Action Limits			Reference Concentrations				
		Sensitive Materials	General Collections	High	Extremely High		Natural Background Levels	Urban Areas	Health: Acute Toxicity Level for 1 h Exposure	EPA Clean Air Act Limits	World Health Organization TWA Limits
Organic acids	Acetic acid,[k] CH_3COOH	<5	224 / 40 to 280	200 to 480	600 to 1000		0.1 to 4	0.1 to 16	OSHA: 10 ppm		
Organic acids	Formic acid,[l] HCOOH	<5	42 to 78	104 to 260	260 to 780		0.05 to 4	0.05 to 17	OSHA: 5 ppm		
Aldehydes	Formaldehyde, HCHO	<0.1 to 5	10 to 20	16 to 120	160 to 480		0.4 to 1.6	1.6 to 24 New home: 50 to 60	75 OSHA: 750		80 (30 min)
Aldehydes	Acetaldehyde,[m] CH_3CHO	<1 to 20						3 to 17	5 OSHA 200 ppm		
	Total VOCs (as hexane)[n]		<100	700	1700			New or renovated building 4500 to 9000			
	Fine particles[o] (PM2.5)	<0.1 µg/m³	1 to 10 µg/m³	10 to 50	50 to 150		1 to 30	1 to 100			

Notes for Table 5

Note: This extrapolation of minimum risk for most collections over an extended period of exposition assumes temperature between 68 and 86°F, collection cleanliness, and less than 60% rh; hypersensitive objects such as lead, vulcanized natural rubber, silver, and most sensitive colorants are excluded and require special control measures.

Source: Grzywacz (2006)

See References:

1. World Health Organization 2000	6. Graedel, Kammlott, and Franey 1981	11. Granby and Christensen 1997	15. Rothweiler, Waeger, and Schlatter 1992
2. Seinfeld 1986	7. Sano 1999	12. Grosjean and Williams 1992	16. Lavédrine 2003
3. Graedel 1984	8. Sano 2000	13. Hodgson et al. 2000	17. National Air Filtration Association
4. Tétreault 2003	9. Bradley and Thickett 1999	14. Office of Environmental Health Hazard	(NAFA) 2004
5. Grosjean 1988	10. Kawamura, Steinberg, and Kaplan 1996	Assessment 2003	

[a]Current standards, based on best available sources; not meant to be absolute and final concentration recommendations. Concentration limits for materials and objects continue to be reviewed. Two sources are CCI (http://www.cci-icc.gc.ca) and the IAQ in Museums and Archives Web site (http://www.IAQ.dk).

[b]Maximum levels allowed to ensure minimum risk to sensitive objects; assumes temperature between 59 and 77°F, clean collection, and less than 60% rh (ideally less than 50%) (Tétreault 2001).

[c]Temperature and relative humidity should always be minimized as well as pollutant concentration to reduce risk.

[d]Mitigation measures should be taken to protect objects in the collection.

[e]Sensitive materials are those that are at risk from the particular gaseous pollutant.

[f]Acute reference exposure levels (RELs) established by U.S. Office of Environmental Health Hazard Assessment (OEHHA 2003).

[g]U.S. Environmental Protection Agency Office of Air and Radiation Clean Air Act limits (EPA 2003).

[h]World Health Organization's maximum exposure recommendations (World Health Organization 2000).

[i]U.S. Department of Labor, Occupational Safety and Health Agency maximum permissible exposure limit (PEL) for 8 h work day.

[j]NO is unstable and breaks down. However, it reacts with ozone to form HNO_2, nitrous acid, which is damaging. Eliminate O_3 to reduce risk from NO.

[k]Acetic acid levels can be as high as 10,000 ppb inside enclosures made with inappropriate materials.

[l]Very little is known about effects of formic acid at various concentrations.

[m]Little damage has been directly attributed to acetaldehyde.

[n]Total VOCs are reported referenced to calibrated gas, such as hexane or toluene.

[o]Adapted from Tétreault (2003).

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collection needing higher humidity does not dominate a building, but only a manageable minority of the spaces, then separate humidified storage containers, cases, cabinets, or rooms are an alternative. These must be carefully sealed and isolated to preserve their internal environment and to protect the building from the moisture.

Reliability. Most collections can tolerate several hours of lost conditions without major damage, but some are at risk even with brief losses of control. The engineer should evaluate equipment failure scenarios against collection sensitivities and likely maintenance efforts to see what reasonable precautions can be taken to minimize downtime and damage to the collection. Spare equipment may need to be kept at the project site to allow timely repairs.

Loads. Certain load characteristics of collection buildings should be considered in system design. Usually, the HVAC system should operate 24 h/day. Galleries and reading rooms tend to have high occupancy only at certain times. Some gallery occupancies are as high as 10 ft^2 per person, but stack or storage areas may have 1000 ft^2 per person or less. The system should be designed to handle this load as well as the more common part-loads. Many engineers design to 20 ft^2 per person because part of the room is never occupied. In other facilities, where the space is extensively used for receptions, openings, and other high-traffic activities, even higher density assumptions may be justified. Continual and close dialogue between the designer and client is therefore important.

Lighting loads vary widely from space to space and at different times of the day. The most common driver of sizing cooling in a museum is display lighting. The engineer should ensure that estimated lighting loads are realistic. Lighting typically varies from 2 to 8 W/ft^2 for display areas; figures as high as 15 W/ft^2 are sometimes requested by lighting designers, but are rarely needed. With growing awareness of damage caused by light, display areas for light-sensitive objects should have low illumination levels, and associated low lighting power densities.

Exhibit Cases. Exhibit cases should be designed to protect the collection from environmental extremes and excesses. Sealed or vented cases are typically used. Sealed cases rely on isolation from the ambient environment in the exhibition room and usually require passive or special conditioning systems independent of regular room air. Because sealed cases are subject to build-up of gaseous contaminants, they should be made of inert or low-emission materials, or those that emit gases benign to objects in the case. In a properly conditioned space, exhibit cases that are within, built into, or back up to this space can be vented.

Exhibit cases should not be conditioned by blowing supply air into the cases, or by drawing return air through the cases. Supply air temperature and humidity vary and can cause extremes if blown into a case. Even if temperature and humidity conditions are sensed inside the case as part of the control system, the typical high ratio of supply air to the case volume makes such treatments problematic. Acute temperature or humidity conditions in supply air are undiluted and immediately affect sensitive objects. Return air is more stable but tends to have higher levels of particulate contamination, leading to particle accumulation in the display case. Active conditioning of exhibit cases has been used successfully, but only by using purpose-designed equipment.

These systems are not configured like typical HVAC systems and have additional features, such as desiccant beds to stabilize supply air humidity. They are used primarily in cold climates, where conditioning large, historic galleries is problematic and case conditioning is often the only solution. Condition stability with these systems is less than ideal, and much less than sealed exhibit cases with passive conditioning agents. The primary value is where many cases need to be conditioned and rigorous sealing and reconditioning passive agents are impractical. Lights should always be housed in a separate ventilated compartment from the one housing the artifacts.

Cold Storage Vaults. Cold storage vaults extend the life of materials particularly sensitive to thermal deterioration, such as acetate films and color photographic materials. These vaults usually require special equipment; experienced turnkey or design-build vendors provide the most successful systems (Lavédrine 2003; Wilhelm 1993).

Primary Elements and Features

The following primary HVAC elements and features provide a good preservation environment for a museum or library, as in Figure 6 (Lull 1990).

Constant Air Volume. Air should be constantly circulated at sufficient volume, regardless of tempering needs, to ensure good circulation throughout the collection space. In general, perimeter radiation and other sensible-only heating or cooling elements should be avoided, because they can create local humidity extremes near collections.

Cooling System. Several systems are available, including direct expansion (DX) cooling, glycol, and central chilled water. Screw compressors are recommended to generate chilled water at 36°F for use in chilled-water coils, which generally have copper fins and tubes. Conventional, DX, and chilled-water systems have a limitation in producing 36°F chilled water; therefore, desiccant systems may be considered instead. Ice storage systems with glycol also could be used.

Heating System. Several systems are available to generate heat, including steam and oil with converter, modular boilers, and scotch marine boilers. Hot water is circulated through heating and reheat coils for temperature and humidity control in the space.

Humidification. Humidification should be provided by steam or deionized water introduced in the air system. Evaluate the moisture source for contamination potential. Often, heating steam is treated with compounds (especially amines) that can pose a risk to the collection (Volent and Baer 1985). Systems should be selected and designed to prevent standing pools of water, and should follow good humidification design as described in Chapters 1 and 20 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*. Humidification methods include electronic steam humidifiers, clean steam humidifiers, evaporative pan humidifiers, spray-coil wetted-element systems, and ultrasonic humidification. All materials in humidification equipment should be selected to minimize microbial growth and degradation of system components.

Unlike most other applications, HVAC design for this building type is often more concerned with humidity control than temperature control. The averaging effect of a common mixed return air and common humidifier on a central system is preferred, but sometimes zone humidifiers have been necessary to recover from unsatisfactory conditions, even when the same humidity level is desired in each zone on the same system. Attempt to identify and correct the cause of the condition before taking drastic measures.

Maintaining widely different conditions in zones using the same air handler can be difficult to achieve, and wastes energy. If possible, different zone conditions should have the same absolute moisture content, using zone reheat to modify space humidity for different relative humidity requirements.

Fig. 6   Primary Elements of Preservation Environment HVAC System

Dehumidification. The most common problem in museums and libraries is inadequate or ineffective dehumidification. Modest dehumidification can be achieved with most cooling systems, limited by the apparatus dew point at the cooling coil, and requiring adequate reheat. Most problems derive from compromises in the cooling medium temperature or lack of reheat. Some chilled-water systems may not reliably deliver water that is cold enough, or may have chilled-water temperature reset or cooling coils that are too shallow for dehumidification to occur. Zone reheat is essential to maintaining necessary conditions in the space.

Sebor (1995) suggests the following typical approaches to more aggressive dehumidification:

- **Low-temperature chilled water**, usually based on a glycol solution, offers familiar operation and stable control but requires glycol management.
- **DX refrigeration** tends to be better for small systems and has lower capital costs, but generally is less reliable, requires more energy, and may require a defrost cycle.
- **Desiccant dehumidifiers** can be quite effective if properly designed, installed, and maintained. Economy of operation is very sensitive to the cost of the regeneration heat source. Liquid desiccant systems eliminate (1) the need to cool the air below the dew point, and (2) reheat, both of which are very important cost factors for sustainability.

Desiccant systems (Figure 7) may be a good solution in many cases that require humidity between 30 and 35% rh year-round. Desiccant regeneration is required. Silica gel and rotary wheel dehumidifiers are commonly used. Dehumidification systems should be additions to a typical cooling system; they cannot maintain comfort conditions by themselves. For libraries or archives requiring cool, dry conditions, a desiccant system may be required. Chapter 22 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment* has further information on desiccants.

Outside Air. Because the goal is to maintain a close-tolerance environment, excessive amounts of outside air for economizer cooling are problematic. Outside air is almost always at nondesign temperature and humidity, and can introduce particles and gaseous pollution. Economizer cooling is often the primary cause of humidity fluctuations in museums and libraries and requires very large humidification systems; air-side economizers should not be used unless (1) bin analysis or other study shows outside air moisture content to be favorable for an economical number of hours, and (2) favorable outside air can be reliably selected by the control system. Outside air should be the minimum amount required to provide fresh air for occupants and to pressurize collection spaces. Relief air (see Figure 6) usually should not be used, unless required to support
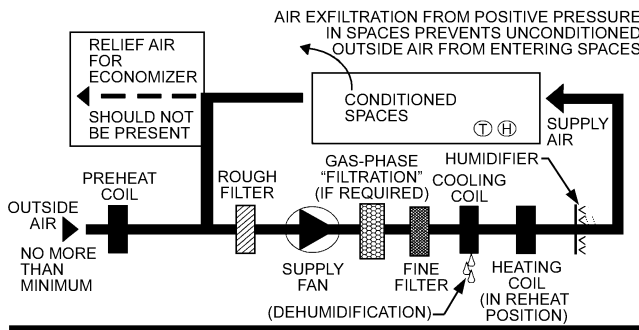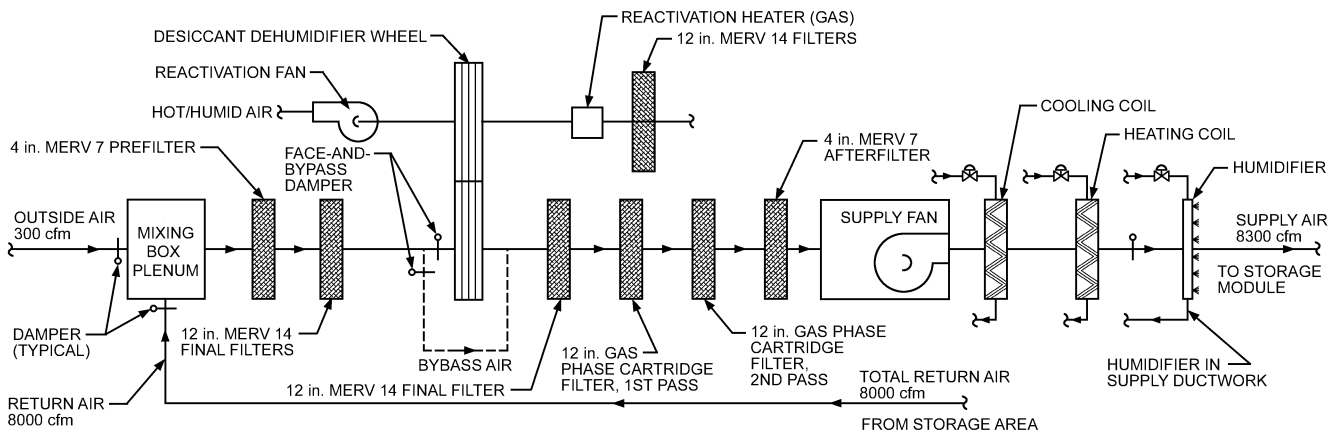
Fig. 7   Packaged Desiccant Dehumidification Unit
(Setty 2006)

high outside-air requirements for high occupancy. Peak occupancies are rarely the norm, so outside air might be controlled by monitoring levels of carbon dioxide or other gases indicative of occupancy.

The added cost of preconditioning outside air, usually with a precooling coil, often benefits humidity control and economical operation. Cooling can reduce the amount of reheat needed for dehumidification, and may reduce static pressure on the primary fan by keeping the cooling coil dry.

Filtration

Particulate Filtration. Particulate filtration is essential for removal of contaminants that could foul the HVAC system, as well as particles that might degrade or deface artifacts being preserved. For this reason, particulate filtration is addressed here in two steps: prefiltration and fine-particulate filtration.

Prefiltration is required for to prevent fouling in cooling coils and build-up of dust in the fan, ductwork, or other HVAC components. It is also required to protect and prolong the functional service life of gas-phase filters and fine-particulate filters. These fouling-sized particles are generally considered to be the MERV E-3 (ASHRAE *Standard* 52.2) range particles or the 3 to 10 µm size range. Achieving at least 50% removal of the E-3 particle size range requires MERV 7 filtration.

Higher efficiencies may be possible with media configurations that operate at lower pressure loss. MERV 11 or higher prefilters can operate at similar or lower pressure drop and provide more protection for HVAC components and gas-phase filters.

Fine-particulate filtration protects artifacts and collections in the facility. This particle size is commonly referred to as the "accumulation" size and falls in the MERV E-1 range of particles (0.3 to 1 µm). Removal efficiencies of a minimum of 85% of the E-1 range are sufficient for preservation of most collections. MERV 15 filters are minimum 85% in the E-1 range, and minimum 90% in both the E-2 (1 to 3 µm) and E-3 (3 to 10 µm) ranges.

Some collections require higher efficiencies than MERV 15 for long-term preservation. Options include microenclosures with minimal airflow and separate filtration, or HEPA (99.97% at 0.3 µm) filtration for the entire common area. Whenever HEPA filtration is used as the final filtration, serious consideration should be given to upgrading the prefiltration to protect the life of the HEPA filters.

Framing systems should be able to seal the air filters without bypass air leakage in the housing. Systems design with positive locking mechanisms for filters is a benefit.

High-voltage electrostatic air cleaners should be used with caution because of the potential to generate ozone, which can damage artifacts (see Table 2).

Gas-Phase Filtration. Outside air infiltration of gaseous pollutants, materials offgassing in new construction, and similar offgassing of furnishings and cleaning agents may threaten the stability of some collections. Sensitive collections of valuable holdings (e.g., low-fire ceramics, some metals and alloys, film, rare books) should use active control of gas-phase contaminants.

The primary compounds of concern include acetic acid, formaldehyde, hydrogen sulfide, nitrogen dioxide, ozone, and sulfur dioxide, all of which are removable with molecular filtration. The specific sorbent must be chosen for the various gaseous contaminants indigenous to the facility, because removal and retention properties are not all the same. Some gases are easily removed with activated carbon, whereas others may require treated carbon or potassium permanganate beds.

Careful thought should be given to the service life of molecular filtration media. Much service life testing has focused on the potential weight removal capacity of the sorbent when immersed in a challenge chemical; although this information is important, removal from an airstream may not be achievable even though the sorbent is not spent.

Air Distribution. High, monumental spaces are prone to thermal stratification. If this places collections at risk, then appropriate return and supply air may be required to ensure air motion across the entire space. Gallery and display area use and loads may change because of varied lighting and numbers of visitors. Although this can sometimes be addressed through temperature control zones, adjustable supply air may be more economical and more effective.

Supply air should not blow directly onto collections. Diffusing supply air along a wall can be a major problem in a gallery, where collections are displayed on walls. Floor supply should also be avoided because particles at foot level become entrained.

Controls. Control system design is critical for maintaining precise temperature and humidity control. Consideration should be given to industrial-grade controls for proper temperature and humidity. Control systems should be able to monitor and control humidity, temperatures, airflow, filter pressure drops, water alarms, capacity alarms, and failure scenarios.

Sensors, thermostats, and humidistats must be located in the collection space, not in the return airstream. Temperature variation is usually preferable to prolonged humidity swings. This strongly affects controls design, because conventional control treats temperature as the primary goal and humidity as supplementary. Where comfort conditions are not required, humidity-controlled heating, which modulates heating within a very broad temperature dead band to seek stable or moderated humidity conditions, might be used (LaFontaine 1982; Marcon 1987; Staniforth 1984). By tracking system performance using the temperature control system, operators can adjust zones based on actual operating history. Operating at lower system volume at night when lights are off, but maintaining more than 6 air changes per hour, can save energy.

Types of Systems

The type of HVAC system used is critical to achieving project environmental goals. Proper airflow filters the air, controls humidity, and suppresses mold growth. Minimum airflow criteria vary from 6 to 8 air changes per hour (NBS 1983; Chapter 3 of this volume). These needs are usually best met with a constant-volume system.

The problems most often overlooked are maintenance access and risk to the collection from disruptions and leaks from overhead or decentralized equipment. Water or steam pipes over and in collection areas present the possibility of leaks, as do air-handling units. Some systems can provide full control without running any pipes to the zones, but others require two to six pipes to each zone, which often must be run over or in collection areas and are, unfortunately, the pipes most likely to leak. Leaks and maintenance can prevent effective use of spaces and result in lost space efficiency.

Central air-handling stations keep filtration, dehumidification, humidification, maintenance, and monitoring away from the collection. The investment in added space and the expense of the more elaborate duct system provide major returns in reduced disruption to the collection spaces and a dramatically extended service life for the distribution system. Unlike most commercial projects, space turnover in museums is low and rezoning is rarely needed. In some museums, 60-year-old multizone duct systems have been reused. Renovating the old system is economical, with most renovations confined entirely to the mechanical rooms. This is in comparison to common duct distribution systems (e.g., terminal reheat, dual-duct, and variable-air-volume), where renovations often require a new duct system and terminal equipment, involving major expense from demolishing the old ducts, installing the new duct system, and reinstalling architectural finishes.

Constant-Volume Reheat. A constant-volume reheat system can present problems if improperly applied. In many institutions, terminal reheat with steam or hot-water coils located near or over collection spaces cause chronic problems from steam and water leaks. Efficient zone-level humidification often suggests placing the humidifier downstream from the reheat coil; if the reheat coil is

located near or over collection spaces, preventive maintenance on humidifiers further complicates maintenance problems. Constant-volume reheat systems are very effective when reheat coils and humidifiers are installed entirely within the mechanical space, instead of at the terminal, feeding through what is effectively a multizone distribution system.

Multizone System. A multizone air handler with zone reheat and zone humidification can be a stable and relatively energy-efficient solution. However, multizone systems without individual zone reheat and individual zone humidification have proved problematic in many institutions, requiring retrofit of zone equipment for stable humidity control. With proper layout and equipment complement, a multizone system can reduce the amount of reheat and be very energy-efficient.

Bovill (1988, Figure 10) shows preferences for constant-volume and multizone systems in collection spaces. Without the need for many temperature control zones, but with the need for high air quality, the choices are constant-volume, multizone with bypass, and dual-duct. When air handlers are outside collection areas (as recommended), the best choices are constant-volume and multizone with bypass, and dual-duct. When other systems are used, the client must be made fully aware of the possible compromises in performance, cost, and serviceability.

Dehumidification Coil. An important feature of multizone and dual-duct air handlers is a separate dehumidification coil upstream of both the hot and cold decks. This separate cooling coil, distinct from the one in the cold deck, is used during dehumidification demand. Air can be cooled to dew point even if it eventually flows through the hot deck. Without this feature, moist return air could be warmed in the hot deck and delivered back to the room without being dehumidified. An alternative is to locate a single cooling coil upstream of both decks, where the cold deck simply bypasses the hot deck, although this configuration can increase energy use.

Fan-Coil Units. Fan-coil units have been problematic when placed in and above collection areas. Fan-coil units expand and decentralize maintenance, requiring maintenance in collection areas and a net increase in overall facility maintenance. Because they cool locally, they need condensate drains, which can leak or back up over time. As all-water systems, they require four pressurized-water pipes to each unit, increasing the chance of piping leaks in collection areas.

Variable Air Volume (VAV). VAV, though appropriate for other types of buildings, tends to be inappropriate for collection housing because of poor humidity control, inadequate airflow, maintenance disruption, leaks in the collection spaces, and inflexibility to meet environmental needs. A VAV system may be chosen because of space and budget constraints, but almost always the cost and space required for a properly designed VAV system (full filtration, local humidification, local dehumidification, minimum air volume settings, well-planned piping and maintenance access, well-documented operating instructions) give no advantages over constant-volume systems. VAV systems can save energy compared to constant-volume systems, but usually at the collection's expense.

If used, a VAV system should look much like a constant-volume reheat system, with the minimum airflow to prevent mold growth, contamination buildup, and uneven conditions in the conditioned space. Terminal equipment should include reheat for each zone and be located in mechanical rooms or other spaces where access and service do not endanger a collection. If VAV performance becomes a problem, it can be easily converted to a constant-volume reheat system with only an adjustment of controls.

Fan-Powered Mixing Boxes. These are usually inappropriate for these facilities. Although fan-powered mixing boxes can help ensure air circulation to suppress mold growth, they do not allow effective air filtration for particles and gases. These fans also increase local maintenance requirements and present an added fire

risk. If they include reheat, there is an added risk from leaks (with water or steam reheat) or fire (with electric reheat).

Energy and Operating Costs

Operating a preservation environment is often costly, but it is necessary for long-term protection of a valuable collection. In most cases, the increase in usable life of a collection easily justifies the annual energy and operating costs to maintain the special environmental conditions. For institutions with small or limited operating budgets that cannot afford a major increase in annual energy cost, some compromises might be warranted or some initial capital investments made to reduce recurring annual costs. Careful commissioning using multiple instruments is helpful, and postconstruction tuning and off-hours volume reduction can reduce fan energy.

Scope of Special Environments. One of the best ways to reduce operating costs is to treat as little of the building as possible with the special environments. Spaces not needing preservation conditions should be on separate air systems that operate only when occupied.

Energy Efficiency. Using condenser heat to provide reheat for dehumidification can increase efficiency, and can substantially reduce dehumidification energy cost. Although an air-side economizer can cause problems, a water-side economizer can allow efficient winter cooling using condenser water. Because load varies between day and night operations, particularly in museums, night cooling loads are sometimes best met with a smaller off-hours chiller. Similarly, primary-secondary pumping with two-way control valves can be useful as loads vary over the day and across areas.

Daylighting. Using natural light is often proposed. Ayres et al. (1990) noted that this feature is always a net energy penalty. If used, the daylighting aperture should be minimized, and avoided as much as possible in and over collection areas. For lower risk of leaks and better-managed lighting, clerestories are preferred over skylights.

Humidistatically Controlled Heating. This specialized approach has limited application and must include safety controls, but is sometimes the only option that can handle envelope limitations in cold climates. In this approach, the heating system is controlled by a humidistat rather than a thermostat (LaFontaine and Michalski 1984); cold, damp air is heated until the relative humidity drops to 50%. Where interior temperatures drop consistently below 50°F, it solves the problem of humidity in a building that does not have an adequate envelope. Obviously, humidity-controlled heating does not provide human comfort in winter, but many small museums, historic buildings, and reserve collection buildings are essentially unoccupied in winter. A high-limit thermostat is necessary to stop overheating during warm weather, and a low-limit thermostat is optional if water pipe freezing is a concern. This approach has been used in Canada (LaFontaine 1982; Marcon 1987), the United States (Conrad 1994; Kerschner 1992, 2006), and in many historic buildings in Britain (Staniforth 1984). Maekawa and Toledo (2001) successfully applied humidistatic control in hot, humid climates to minimize microbial growth.

Some cautions apply. Foundations in a previously heated building may heave if the ground is waterlogged before freezing. Improving drainage, insulating the ground near the footings, and heating the basement reduce this risk. Problems have occurred in buildings with dense object storage and a very low infiltration rate, such as a specially sealed storage space (Padfield and Jensen 1996); a very slow supply of dehumidified air to the space can be helpful.

This approach is cost-effective in seasonal museums (especially for low-mass wood-frame buildings) in colder climates like the northern United States and Canada, and in maritime regions. Humidistat control does not work in warm, humid weather: without a high-limit thermostat it can heat hot, humid conditions to dangerous temperatures. In this case, domestic dehumidifiers can supplement humidistat control.

Hybrid (Load-Sharing) HVAC Systems. This approach involves enhancing preservation in museums and libraries by an optimum

collocation of radiant and forced-convection systems. Most of the sensible loads are assigned to radiant panel systems, whereas latent loads and the remaining sensible loads are assigned to forced-convection systems. Decoupling the HVAC functions primarily into sensible and latent heat transfer components enables the designer to select better function-oriented HVAC components and to ensure higher accuracy and precision in control. Additionally, hybrid HVAC seems to satisfactorily balance the needs of preservation and human comfort, while keeping operating costs low. For example, in a library, human comfort could be maintained primarily by thermal radiation, while lowered air temperature increased the expected half-life of the books, with required fan power reduced by almost 50% (Kilkis et al. 1995). Moreover, because the forced-convection system is freed from satisfying most of the sensible heating and cooling loads, more accurate humidity control and faster response to humidity changes may be achieved. Multizoning in a hybrid HVAC system may be easier. Latent and sensible systems can also be integrated into a single HVAC unit called a **hybrid panel** (Kilkis 2002). When hydronic radiant panels, which require piping fluids into exhibition areas, are used, associated risks of damage from liquid leaks and the greater maintenance challenges must be balanced against expected savings. Liquid leakage risk might be minimized by using capillary tubing operated under negative pressure. To eliminate liquid leakage risks, all-air hybrid HVAC systems may be used. More information about panel heating and cooling and hybrid HVAC systems can be found in Chapter 6 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*.

Maintenance and Ease of Operation. A common failing of designs is not accounting for ongoing operation and maintenance. Most designs work if properly adjusted and maintained, but many institutions do not have the staff, budget, or expertise to give the system the attention it needs. Maintenance needs for any system should be matched against the institution's staff capabilities. For large projects in larger cities, code-required staffing for the plant should be considered; sometimes, smaller reciprocating chillers can be used at night to preclude the licensed engineer needed to operate larger chillers. Small projects without HVAC maintenance staff may need packaged equipment that does not require daily attention.

Effects of maintenance activities on the collection must always be taken into account. For example, testing or accidental activation of a smoke removal system can radically change the collection environment. Transitions between winter and summer modes on economizers cause many operational problems. Tools and ladders in gallery and storage areas are a threat to the collection and special precautions need to be taken.

Contaminated air conveyance components (e.g., microbiological growth and other buildup) can contribute to pollution levels, lead to premature component failure, and affect heat transfer efficiency, resulting in higher utility costs. Regular inspection and cleaning is an important part of preventative maintenance.

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CHAPTER 22

ENVIRONMENTAL CONTROL FOR ANIMALS AND PLANTS

THE design of plant and animal housing is complicated because many environmental factors affect the production and well-being of living organisms. The financial constraint that equipment must repay costs through improved economic productivity must be considered by the designer. The engineer must balance costs of modifying the environment against economic losses of a plant or animal in a less-than-ideal environment.

Thus, design of plant and animal housing is affected by (1) economics, (2) concern for both workers and the care and well-being of animals, and (3) regulations on pollution, sanitation, and health assurance.

DESIGN FOR ANIMAL ENVIRONMENTS

Typical animal production plants modify the environment, to some degree, by housing or sheltering animals year-round or for parts of a year. The degree of modification is generally based on the expected increase in production. Animal sensible heat and moisture production data, combined with information on the effects of environment on growth, productivity, and reproduction, help designers select optimal equipment (see Chapter 10 of the 2005 *ASHRAE Handbook—Fundamentals*). Detailed information is available in a series of handbooks published by the MidWest Plan Service. These include *Mechanical Ventilating Systems for Livestock Housing* (MWPS 1990a), *Natural Ventilating Systems for Livestock Housing and Heating* (MWPS 1989), and *Cooling and Tempering Air for Livestock Housing* (MWPS 1990b). ASAE *Monograph* 6, Ventilation of Agricultural Structures (Hellickson and Walter 1983), also gives more detailed information.

Design Approach

Environmental control systems are typically designed to maintain thermal and air quality conditions within an acceptable range and as near the ideal for optimal animal performance as is practicable. Equipment is usually sized assuming steady-state energy and mass conservation equations. Experimental measurements confirm that heat and moisture production by animals is not constant and that there may be important thermal capacitance effects in livestock buildings. Nevertheless, for most design situations, the steady-state equations are acceptable.

Achieving the appropriate fresh air exchange rate and establishing the proper distribution within the room are generally the two most important design considerations. The optimal ventilation rate is selected according to the ventilation rate logic curve (Figure 1).
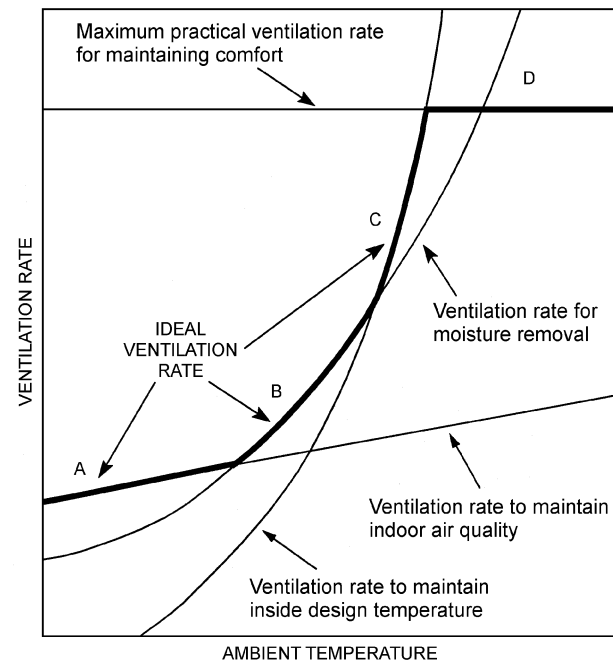
Fig. 1   Logic for Selecting Appropriate Ventilation Rate in Livestock Buildings
(Adapted from Christianson and Fehr 1983)

During the coldest weather, the ideal ventilation rate is that required to maintain indoor relative humidity at or below the maximum desired, and air contaminant concentrations within acceptable ranges (Rates A and B in Figure 1). Supplemental heating is often required to prevent the temperature from dropping below optimal levels.

In milder weather, the ventilation rate required for maintaining optimal room air temperature is greater than that required for moisture and air quality control (Rates C and D in Figure 1). In hot weather, the ventilation rate is chosen to minimize the temperature rise above ambient and to provide optimal air movement over animals. Cooling is sometimes used in hot weather. The maximum rate (D) is often set at 60 air changes per hour (ach) as a practical maximum.

Temperature Control

The temperature in an animal structure is computed from the sensible heat balance of the system, usually disregarding transient effects. Nonstandard buildings with low airflow rates and/or large thermal mass may require transient analysis. Steady-state

heat transfer through walls, ceiling or roof, and ground is calculated as presented in Chapter 25 of the 2005 *ASHRAE Handbook—Fundamentals*.

Mature animals typically produce more heat per of unit floor area than do young stock. Chapter 10 of the 2005 *ASHRAE Handbook—Fundamentals* presents estimates of animal heat loads. Lighting and equipment heat loads are estimated from power ratings and operating times. Typically, the designer selects indoor and outdoor design temperatures and calculates the ventilation rate to maintain the temperature difference. Outdoor design temperatures are given in Chapter 28 of the 2005 *ASHRAE Handbook—Fundamentals*. The section on Recommended Practices by Species in this chapter presents indoor design temperature values for various livestock.

Moisture Control

Moisture loads produced in an animal building may be calculated from data in Chapter 10 of the 2005 *ASHRAE Handbook—Fundamentals*. The mass of water vapor produced is estimated by dividing the animal latent heat production by the latent heat of vaporization of water at animal body temperature. Spilled water and evaporation of fecal water must be included in the estimates of latent heat production within the building. The amount of water vapor removed by ventilation from a totally slatted (manure storage beneath floor) swine facility may be up to 40% less than the amount removed from a solid concrete floor. If the floor is partially slatted, the 40% maximum reduction is decreased in proportion to the percentage of the floor that is slatted.

Ventilation should remove enough moisture to prevent condensation but should not reduce the relative humidity so low (less than 40%) as to create dusty conditions. Design indoor relative humidity for winter ventilation is usually between 70 and 80%. The walls should have sufficient insulation to prevent surface condensation at 80% rh inside.

During cold weather, ventilation needed for moisture control usually exceeds that needed to control temperature. Minimum ventilation must always be provided to remove animal moisture. Up to a full day of high humidity may be allowed during extremely cold periods when normal ventilation rates could cause an excessive heating demand. Humidity level is not normally the controlling factor in mild or hot weather.

Air Quality Control

Contaminants. The most common and prevalent air contaminants in animal buildings are particulate matter (PM) and gases. In animal buildings, particulate matter originates mainly from feed, litter, fecal materials, and animals. Particulates include solid particles (or dust), liquid droplets, and microorganisms, can be deposited deep within the respiratory system. Particulates carry allergens that cause discomfort and health problems for workers in animal housing facilities. They also carry much of the odors in animal housing facilities, for potentially long distances from the facilities. Consequently, particulates pose major problems for animals, workers, and neighbors. Particulate levels in swine buildings have been measured to range from 0.028 to 0.43 mg/ft^3. Dust has not been a major problem in dairy buildings; one two-year study found an average of only 0.014 mg/ft^3 in a naturally ventilated dairy barn. Poultry building dust levels average around 0.057 to 0.20 mg/ft^3, but levels up to 0.51 to 0.82 mg/ft^3 have been measured during high activity.

The most common gas contaminants are ammonia, hydrogen sulfide, other odorous compounds, carbon dioxide, and carbon monoxide. High moisture levels can also aggravate other contaminant problems. Ammonia, which results from decomposition of manure, is the most important chronically present contaminant gas. Typical ammonia levels measured have been 10 to 50 ppm in poultry units, 0 to 20 ppm in cattle buildings, 5 to 30 ppm in swine units with liquid manure systems, and 10 to 50 ppm in swine units with

solid floors (Ni et al. 1998a). Up to 200 ppm have been measured in swine units in winter. Ammonia should be maintained below 25 ppm and, ideally, below 10 ppm.

Maghirang et al. (1995) and Zhang et al. (1992) found ammonia levels in laboratory animal rooms to be negligible, but concentrations could reach 60 ppm in cages. Weiss et al. (1991) found ammonia levels in rat cages of up to 350 ppm with four male rats per cage and 68 ppm with four female rats per cage. Hasenau et al. (1993) found that ammonia levels varied widely among various mouse microisolation cages; ammonia ranged from negligible to 520 ppm nine days after cleaning the cage.

Hydrogen sulfide, a by-product of microbial decomposition of stored manure, is the most important acute gas contaminant. During normal operation, hydrogen sulfide concentration is usually insignificant (i.e., below 1 ppm). A typical level of hydrogen sulfide in swine buildings is around 150 to 350 ppb (Ni et al. 1998b). However, levels can reach 200 to 330 ppm, and possibly up to 1000 to 8000 ppm during in-building manure agitation.

Odors from animal facilities are an increasing concern, both in the facilities and in the surrounding areas. Odors result from both gases and particulates; particulates are of primary concern because odorous gases can be quickly diluted below odor threshold concentrations in typical weather conditions, whereas particulates can retain odor for long periods. Methods that control particulate and odorous gas concentrations in the air also reduce odors, but controlling odor generation at the source appears to be the most promising method of odor control.

Barber et al. (1993), reporting on 173 pig buildings, found that carbon dioxide concentrations were below 3000 ppm in nearly all instances when the external temperature was above 32°F but almost always above 3000 ppm when the temperature was below 32°F. The report indicated that there was a very high penalty in heating cost in cold climates if the maximum allowed carbon dioxide concentration was less than 5000 ppm. Air quality control based on carbon dioxide concentrations was suggested by Donham et al. (1989). They suggested a carbon dioxide concentration of 1540 ppm as a threshold level, above which symptoms of respiratory disorders occurred in a population of swine building workers. For other industries, a carbon dioxide concentration of 5000 ppm is suggested as the time-weighted threshold limit value for 8 h of exposure (ACGIH 1998).

Other gas contaminants can also be important. Carbon monoxide from improperly operating unvented space heaters sometimes reaches problem levels. Methane is another occasional concern.

Control Methods. Three standard methods used to control air contaminant levels in animal facilities are

1. Reduce contaminant production at the sources.
2. Remove contaminants from the air by air cleaning.
3. Reduce contaminant concentration by dilution (ventilation).

The first line of defense is to reduce release of contaminants from the source, or at least to intercept and remove them before they reach workers and animals. Animal feces and urine are the largest sources of contaminants, but feed, litter, and the animals themselves are also a major source of contaminants, especially particulates. Successful operations effectively collect and remove all manure from the building within three days, before it decomposes enough to produce large quantities of contaminants. Removing ventilation air uniformly from manure storage or collection areas helps remove contaminants before they reach animal or worker areas.

Ammonia production can be minimized by removing wastes from the room and keeping floor surfaces or bedding dry. Immediately covering manure solids in gutters and pits with water also reduces ammonia, which is highly soluble in water. Because adverse effects of hydrogen sulfide on production begin to occur at 20 ppm, ventilation systems should be designed to maintain hydrogen sulfide levels below 20 ppm during agitation. When manure is agitated and removed from the storage, the building should be well ventilated and

all animals and occupants evacuated to avoid potentially fatal concentrations of gases.

For laboratory animals, changing the bedding frequently and keeping the bedding dry with lower relative humidities and appropriate cage ventilation can reduce ammonia release. Individually ventilated laboratory animal cages or placing cages in mass air displacement units reduce contaminant production by keeping litter drier. Using localized contaminant containment work stations for dust-producing tasks such as cage changing may also help. For poultry or laboratory animals, the relative humidity of air surrounding the litter should be kept between 50 and 75% to reduce particulate and gas contaminant release. Relative humidities between 40 and 75% also reduce the viability of pathogens in the air. A moisture content of 25 to 30% (wet basis) in the litter or bedding keeps dust to a minimum. Adding 0.5 to 2% of edible oil or fat can significantly reduce dust emission from the feed. Respirable dust (smaller than 10 μm), which is most harmful to the health and comfort of personnel and animals, is primarily from feces, animal skins, and dead microorganisms. Respirable dust concentration should be kept below 0.0065 mg/ft^3. Some dust control technologies are available. For example, sprinkling oil at 0.12 gal per 1000 ft^2 of floor area per day can reduce dust concentration by more that 80%. High animal activity levels release large quantities of particulates into the air, so management strategies to reduce agitation of animals are helpful.

Methods of removing contaminants from the air are essentially limited to particulate removal, because gas removal methods are often too costly for animal facilities. Some animal workers wear personal protection devices (appropriate masks) to reduce inhaled particulates. Room air filters reduce animal disease problems, but they have not proven practical for large animal facilities because of the large quantity of particulates and the difficulty in drawing particulates from the room and through a filter. Air scrubbers can remove gases and particulates, but the initial cost and maintenance make them impractical. Aerodynamic centrifugation is showing promise for removing the small particulates found in animal buildings.

Ventilation is the most prevalent method used to control gas contaminant levels in animal facilities. It is reasonably effective in removing gases, but not as effective in removing particulates. Pockets in a room with high concentrations of particulate contaminants are common. These polluted pockets occur in dead air spots or near large contaminant sources. Providing high levels of ventilation can be costly in winter, can create drafts on the animals, and can increase the release of gas contaminants by increasing air velocity across the source.

Disease Control

Airborne microbes can transfer disease-causing organisms among animals. For some situations, typically with young animals where there are low-level infections, it is important to minimize air mixing among animal groups. It is especially important to minimize air exchange between different animal rooms, so buildings need to be fairly airtight.

Poor thermal environments and air contaminants can increase stress on the animals, which can make them more susceptible to disease. Therefore, a good environmental control system is important for disease control.

Air Distribution

Air speed should be maintained below 50 fpm for most animal species in both cold and mild weather. Animal sensitivities to draft are comparable to those of humans, although some animals are more sensitive at different stages. Riskowski and Bundy (1988) documented that air velocities for optimal rates of gain and feed
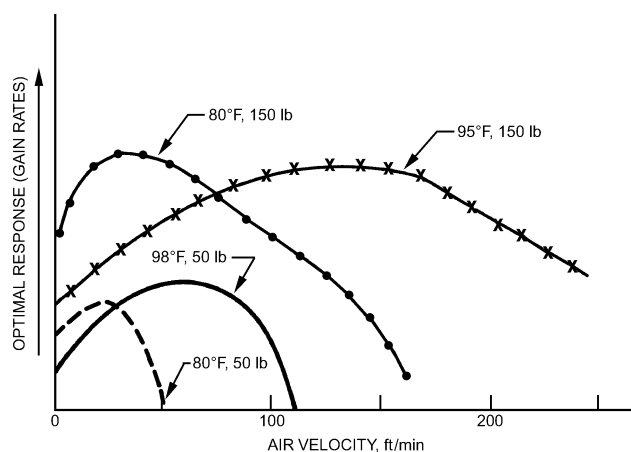
Fig. 2   Response of Swine to Air Velocity

efficiencies can be below 25 fpm for young pigs at thermoneutral conditions.

Increased air movement during hot weather increases growth rates and improves heat tolerance. There are conflicting and limited data defining optimal air velocity in hot weather. Bond et al. (1965) and Riskowski and Bundy (1988) determined that both young and mature swine perform best when air speed is less than 200 fpm (Figure 2). Mount and Start (1980) did not observe performance penalties at air speeds increased to a maximum of 150 fpm.

Degree of Shelter

Livestock, especially young animals, need some protection from adverse climates. On the open range, mature cattle and sheep need protection during severe winter conditions. In winter, dairy cattle and swine may be protected from precipitation and wind with a three-sided, roofed shelter open on the leeward side. The windward side should also have approximately 10% of the wall surface area open to prevent negative pressure inside the shelter, which could cause rain and snow to be drawn into the building on the leeward side. These shelters do not protect against high temperature or high humidity.

In warmer climates, shades often provide adequate shelter, especially for large, mature animals such as dairy cows. Shades are commonly used in Arizona; research in Florida has shown an approximate 10% increase in milk production and a 75% increase in conception efficiency for shaded versus unshaded cows. The benefit of shades has not been documented for areas with less severe summer temperatures. Although shades for beef cattle are also common practice in the southwestern United States, beef cattle are somewhat less susceptible to heat stress, and extensive comparisons of various shade types in Florida have detected little or no differences in daily weight gain or feed conversion.

The energy exchange between an animal and various areas of the environment is illustrated in Figure 3. A well-designed shade makes maximum use of radiant heat sinks, such as the cold sky, and gives maximum protection from direct solar radiation and high surface temperature under the shade. Good design considers geometric orientation and material selection, including roof surface treatment and insulation material on the lower surface.

An ideal shade has a top surface that is highly reflective to solar energy and a lower surface that is highly absorptive to solar radiation reflected from the ground. A white-painted upper surface reflects solar radiation, yet emits infrared energy better than aluminum. The undersurface should be painted a dark color to prevent multiple reflection of shortwave energy onto animals under the shade.
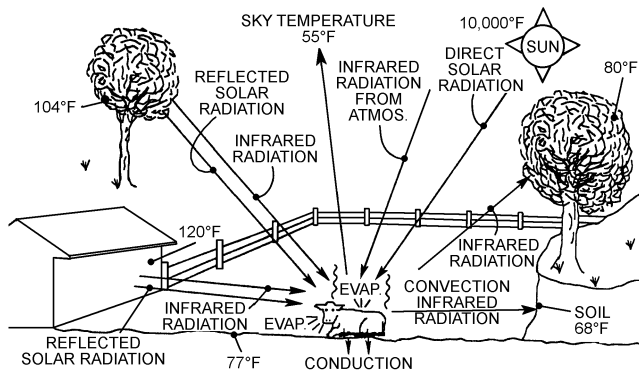
Fig. 3 Energy Exchange Between Farm Animal and Surroundings in Hot Environment

COOLING AND HEATING

Air Velocity

Increasing air velocity helps to facilitate the cooling of mature animals. It is especially beneficial when combined with skin wetting evaporative cooling. Mature swine benefit most with air velocities up to 200 fpm; cattle around 300 fpm; and poultry around 600 fpm. Air velocity can be increased with air circulation fans that blow air horizontally in circular patterns around the room, paddle fans that blow air downward, or tunnel cooling that moves air horizontally along the length of the building.

Evaporative Cooling

Supplemental cooling of animals in intensive housing conditions may be necessary during heat waves to prevent heat prostration, mortality, or serious losses in production and reproduction. Evaporative cooling, which may reduce ventilation air to 80°F or lower in most of the United States, is popular for poultry houses, and is sometimes used for swine and dairy housing.

Evaporative cooling is well suited to animal housing because the high air exchange rates effectively remove odors and ammonia, and increase air movement for convective heat relief. Initial cost, operating expense, and maintenance problems are all relatively low compared to other types of cooling systems. Evaporative cooling works best in areas with low relative humidity, but significant benefits can be obtained even in the humid southeastern United States.

Design. The pad area should be sized to maintain air velocities between 200 and 275 fpm through the pads. For most pad systems, these velocities produce evaporative efficiencies between 75 and 85%; they also increase pressures against the ventilating fans from 0.04 to 0.12 in. of water, depending on pad design.

The building and pad system must be airtight because air leaks caused by the negative-pressure ventilation reduce airflow through the pads, and hence reduce cooling effectiveness.

The most serious problem encountered with evaporative pads for agricultural applications is clogging by dust and other airborne particles. Whenever possible, fans should exhaust away from pads on adjacent buildings. Regular preventive maintenance is essential. Water bleed-off and the addition of algaecides to the water are recommended. When pads are not used in cool weather, they should be sealed to prevent dusty inside air from exhausting through them.

High-pressure fogging with water pressure of 500 psi is preferred to pad coolers for cooling air in broiler houses with built-up litter. The high pressure creates a fine aerosol, causing minimal litter wetting. Timers and/or thermostats control the cooling. Evaporative efficiency and installation cost are about one-half those of a well-designed evaporative pad. Foggers can also be used with naturally ventilated, open-sided housing. Low-pressure systems are not recommended for poultry, but may be used during emergencies.

Nozzles that produce water mist or spray droplets to wet animals directly are used extensively during hot weather in swine confinement facilities with solid concrete or slatted floors. Currently, misting or sprinkling systems with larger droplets that directly wet the skin surface of the animals (not merely the outer portion of the hair coat) are preferred. Timers that operate periodically, (e.g., 2 to 3 min on a 15 to 20 min cycle) help to conserve water.

Mechanical Refrigeration

Mechanical refrigeration can be designed for effective animal cooling, but it is considered uneconomical for most production animals. Air-conditioning loads for dairy housing may require 2.5 kW or more per cow. Recirculation of refrigeration air is usually not feasible because of high contaminant loads in the air in the animal housing. Sometimes, zone cooling of individual animals is used instead of whole-room cooling, particularly in swine farrowing houses, where a lower air temperature is needed for sows than for unweaned piglets. It is also beneficial for swine boars and gestating sows. Refrigerated air, 18 to 36°F below ambient temperature, is supplied through insulated ducts directly to the head and face of the animal. Air delivery rates are typically 20 to 40 cfm per animal for snout cooling, and 60 to 80 cfm per sow for zone cooling.

Earth Tubes

Some livestock facilities obtain cooling in summer and heating in winter by drawing ventilation air through tubing buried 6 to 13 ft below grade. These systems are most practical in the north central United States for animals that benefit from both cooling in summer and heating in winter.

Cooling and Tempering Air for Livestock Housing (MWPS 1990b) details design procedures for this method. A typical design uses 50 to 150 ft of 8 in. diameter pipe to provide 300 cfm of tempered air. Soil type and moisture, pipe depth, airflow, climate, and other factors affect the efficiency of buried pipe heat exchangers. The pipes must slope to drain condensation, and must not have dips that could plug with condensation.

Heat Exchangers

Ventilation accounts for 70 to 90% of the heat losses in typical livestock facilities during winter. Heat exchangers can reclaim some of the heat lost with the exhaust ventilating air. However, predicting fuel savings based on savings obtained during the coldest periods overestimates yearly savings from a heat exchanger. Estimates of energy savings based on air enthalpy can improve the accuracy of the predictions.

Heat exchanger design must address the problems of condensate freezing and/or dust accumulation on the heat-exchanging surfaces. If unresolved, these problems result in either reduced efficiency and/or the inconvenience of frequent cleaning.

Supplemental Heating

For poultry weighing 3.3 lb or more, for pigs heavier than 50 lb, and for other large animals such as dairy cows, body heat of animals at recommended space allocations is usually sufficient to maintain moderate temperatures (i.e., above 50°F) in a well-insulated structure. Combustion-type heaters are used to supplement heat for baby chicks and pigs. Supplemental heating also increases the moisture-holding capacity of the air, which reduces the quantity of air required for moisture removal. Various types of heating equipment may be included in ventilation, but they need to perform well in dusty and corrosive atmospheres.

Insulation Requirements

The amount of building insulation required depends on climate, animal space allocations, and animal heat and moisture production.
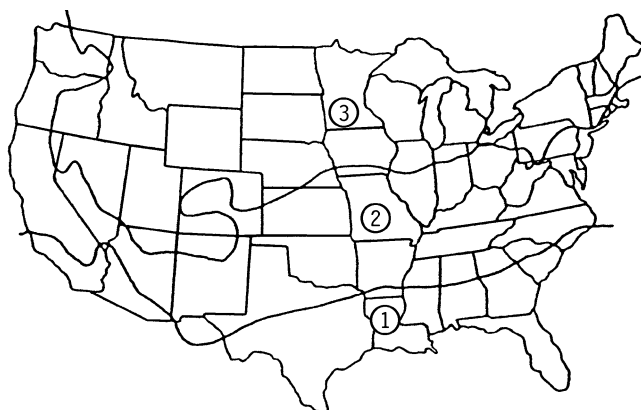
Fig. 4   Climatic Zones
(Reprinted with permission from ASAE *Standard* S401.2)

Table 1   Minimum Recommended Overall Coefficients of Heat Transmission *U* for Insulated Assemblies[a,b]

| Climatic Zone[d] | Recommended Minimum U, Btu/h·ft²·°F[c] | | | | | |
| | Cold | | Modified Environment | | Supplementally Heated | |
	Walls	Ceiling	Walls	Ceiling	Walls	Ceiling
1	—	0.17[e]	0.17[e]	0.071	0.071	0.045
2	—	0.17	0.17	0.059	0.071	0.040
3	—	0.17	0.083	0.040	0.050	0.030

[a]Use assembly U-factors that include framing effects, air spaces, air films, linings, and sidings. Determine assembly U-factors by testing the full assembly in accordance with ASTM *Standard* C1363 or calculate by the procedures presented in the 2005 *ASHRAE Handbook—Fundamentals.*
[b]Values shown are not the values necessary to provide a heat balance between heat produced by products or animals and heat transferred through the building.
[c]Current practice for poultry grow-out buildings uses a U of 0.11 to 0.14 Btu/h·ft²·°F in the roof and walls.
[d]Refer to Figure 4.
[e]Where ambient temperature and radiant heat load are severe, $U = 0.83$ Btu/h·ft²·°F.

Refer to Figure 4 and Table 1 for selecting insulation levels. In warm weather, ventilation between the roof and insulation helps reduce the radiant heat load from the ceiling. Insulation in warm climates can be more important for reducing radiant heat loads in summer than reducing building heat loss in winter.

Cold buildings have indoor conditions about the same as outside conditions. Examples are free-stall barns and open-front livestock buildings. Minimum insulation is frequently recommended in the roofs of these buildings to reduce solar heat gain in summer and to reduce condensation in winter.

Modified environment buildings rely on insulation, natural ventilation, and animal heat to remove moisture and to maintain the inside within a specified temperature range. Examples are warm free-stall barns, poultry production buildings, and swine finishing units.

Supplementary heated buildings require insulation, ventilation, and extra heat to maintain the desired inside temperature and humidity. Examples are swine farrowing and nursery buildings.

VENTILATION

Mechanical Ventilation

Mechanical ventilation uses fans to create a static pressure difference between the inside and outside of a building. Farm buildings use either positive pressure, with fans forcing air into a building, or negative pressure, with exhaust fans. Some ventilation systems use a combination of positive pressure to introduce air into a building and separate fans to remove air. These zero-pressure systems are particularly appropriate for heat exchangers.

Positive-Pressure Ventilation. Fans blow outside air into the ventilated space, forcing humid air out through any planned outlets and through leaks in walls and ceilings. If vapor barriers are not complete, moisture can condense within the walls and ceiling during cold weather. Condensation causes deterioration of building materials and reduces insulation effectiveness. The energy used by fan motors and rejected as heat is added to the building (an advantage in winter, but a disadvantage in summer).

Negative-Pressure Ventilation. Fans exhaust air from the ventilated space while drawing outside air in through planned inlets and leaks in walls, in ceilings, and around doors and windows. Air distribution in negative-pressure ventilation is often less complex and costly than positive- or neutral-pressure systems. Simple openings and baffled slots in walls control and distribute air in the building. However, at low airflow rates, negative pressure ventilation may not distribute air uniformly because of air leaks and wind pressure effects. Supplemental air mixing may be necessary.

Allowances should be made for reduced fan performance caused by dust, guards, and corrosion of louver joints (Person et al. 1979).

Totally enclosed fan motors are protected from exhaust air contaminants and humidity. Periodic cleaning helps prevent overheating. Negative-pressure ventilation is more commonly used than positive-pressure ventilation.

Ventilation should always be designed so that manure gases are not drawn into the building from manure storages connected to the building by underground pipes or channels.

Neutral-Pressure Ventilation. Neutral-pressure (push/pull) ventilation typically uses supply fans to distribute air down a distribution duct to room inlets, and exhaust fans to remove air from the room. Supply and exhaust fan capacities should be matched.

Neutral-pressure systems are often more expensive, but they achieve better control of the air. They are less susceptible to wind effects and to building leakage than positive- or negative-pressure systems. Neutral-pressure systems are most frequently used for young stock and for animals most sensitive to environmental conditions, primarily where cold weather is a concern.

Natural Ventilation

Either natural or mechanical ventilation is used to modify environments in livestock shelters. Natural ventilation is most common for mature animal housing, such as free-stall dairy, poultry growing, and swine finishing houses. Natural ventilation depends on pressure differences caused by wind and temperature differences. Well-designed natural ventilation keeps temperatures reasonably stable, if automatic controls regulate ventilation openings. Usually, a design includes an open ridge (with or without a rain cover) and openable sidewalls, which should cover at least 50% of the wall for summer operation. Ridge openings are about 2 in. wide for each 10 ft of house width, with a minimum ridge width of 6 in to avoid freezing problems in cold climates. Upstand baffles on each side of the ridge opening greatly increase airflow (Riskowski et al. 1998). Small screens and square edges around sidewall openings can significantly reduce airflow through vents.

Openings can be adjusted automatically, with control based on air temperature. Some designs, referred to as flex housing, include a combination of mechanical and natural ventilation usually dictated by outside air temperature and/or the amount of ventilation required.

VENTILATION MANAGEMENT

Air Distribution

Pressure differences across walls and inlet or fan openings are usually maintained between 0.04 and 0.06 in. of water. (The exhaust

fans are usually sized to provide proper ventilation at pressures up to 0.12 in. to compensate for wind effects.) This pressure difference creates inlet velocities of 600 to 1000 fpm, sufficient for effective air mixing, but low enough to cause only a small reduction in fan capacity. A properly planned inlet system distributes fresh air equally throughout the building. Negative pressure ventilation that relies on cracks around doors and windows does not distribute fresh air effectively. Inlets require adjustment, since winter airflow rates are typically less than 10% of summer rates. Automatic controllers and inlets are available to regulate inlet areas.

Positive pressure ventilation, with fans connected directly to perforated air distribution tubes, may combine heating, circulation, and ventilation in one system. Air distribution tubes or ducts connected to circulating fans are sometimes used to mix the air in negative pressure ventilation. Detailed design procedures for perforated ventilation tubes are described by Zhang (1994). However, dust in the ducts is of concern when air is recirculated, particularly when cold incoming air condenses moisture in the tubes.

Inlet Design. Inlet location and size most critically affect air distribution within a building. Continuous or intermittent inlets can be placed along the entire length of one or both outside walls. Building widths narrower than 20 ft may need only a single inlet along one wall. The total inlet area may be calculated by the system characteristic technique, which follows. Because the distribution of the inlet area is based on the geometry and size of the building, specific recommendations are difficult.

System Characteristic Technique. This technique determines the operating points for the ventilation rate and pressure difference across inlets. Fan airflow rate as a function of pressure difference across the fan should be available from the manufacturer. Allowances must be made for additional pressure losses from fan shutters or other devices such as light restriction systems or cooling pads.

Inlet flow characteristics are available for hinged baffle and center-ceiling flat baffle slotted inlets (Figure 5). Airflow rates can be calculated for the baffles in Figure 5 by the following:

For Case A:

$$Q = 285 W p^{0.5} \qquad (1)$$

For Case B:

$$Q = 183 W p^{0.5} \qquad (2)$$

For Case C (Total airflow from sum of both sides):

$$Q = 320 W p^{0.5} (D/T)^{0.08} e^{(-0.867 \, W/T)} \qquad (3)$$

where

    Q = airflow rate, cfm per foot length of slot opening
    W = slot width, in.
    p = pressure difference across the inlet, in. water gage
    D = baffle width, in.
    T = width of slot in ceiling, in.

Zhang and Barber (1995) measured infiltration rates of five rooms in a newly built swine building at 0.12 cfm/ft^2 of surface area at 0.08 in. water gage. Surface area included the area of walls and ceiling enclosing the room. It is important to include this infiltration rate into the ventilation design and management. For example, at 0.12 cfm/ft^2 of surface area, the infiltration represents 1.4 ach. In the heating season, the minimum ventilation is usually about 3 ach. Thus, large infiltration rates greatly reduce the airflow from the controlled inlet and adversely affect the air distribution.

Room Air Velocity. The average air velocity inside a slot-ventilated structure relates to the inlet air velocity, inlet slot width (or equivalent continuous length for boxed inlets), building width, and ceiling height. Estimates of air velocity within a barn, based on
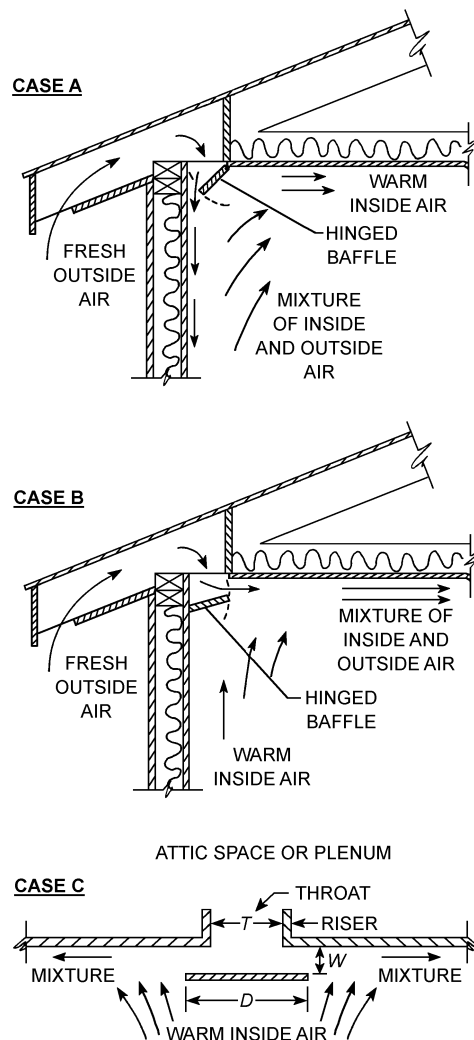
Fig. 5   Typical Livestock Building Inlet Configurations

air exchange rates, may be very low because of the effects of jet velocity and recirculation. Conditions are usually partially turbulent, and there is no reliable way to predict room air velocity at animal level. General design guidelines keep the throw distance less than 20 ft from slots and less than 10 ft from perforated tubes.

Fans

Fans should not exhaust against prevailing winds, especially for cold-weather ventilation. If structural or other factors require installing fans on the windward side, fans rated to deliver the required capacity against at least 0.12 in. of water static pressure and with a relatively flat power curve should be selected. The fan motor should withstand a wind velocity of 30 mph, equivalent to a static pressure of 0.4 in. of water, without overloading beyond its service factor. Wind hoods on the fans or windbreak fences reduce the effects of wind.

Third-party test data should be used to obtain fan performance and energy efficiencies for fan selection (BESS Lab 1997). Fans should be tested with all accessories (e.g., louvers, guards, hoods) in place, just as they will be installed in the building. The accessories have a major effect on fan performance.

Flow Control. Because the numbers and size of livestock and climatic conditions vary, means to modulate ventilation rates are often required beyond the conventional off/on thermostat switch.

The minimum ventilation rate to remove moisture, reduce air contaminant concentrations, and keep water from freezing should always be provided. Methods of modulating ventilation rates include (1) intermittent fan operation (fans operate for a percentage of the time controlled by a percentage timer with a 10 min cycle); (2) staging of fans using multiple units or fans with high/low-exhaust capability; (3) using multispeed fans [larger fans (1/2 hp and up) with two flow rates, the lower being about 60% of the maximum rate]; and (4) using variable-speed fans [split-capacitor motors designed to modulate fan speed smoothly from maximum down to 10 to 20% of the maximum rate (the controller is usually thermostatically adjusted)].

Generally, fans are spaced uniformly along the winter leeward side of a building. Maximum distance between fans is 115 to 165 ft. Fans may be grouped in a bank if this range is not exceeded. In housing with side curtains, exhaust fans that can be reversed or removed and placed inside the building in the summer are sometimes installed to increase air movement in combination with doors, walls, or windows being opened for natural ventilation.

Thermostats

Thermostats should be placed where they respond to a representative temperature as sensed by the animals. Thermostats need protection and should be placed to prevent potential physical or moisture damage (i.e., away from animals, ventilation inlets, water pipes, lights, heater exhausts, outside walls, or any other objects that will unduly affect performance). Thermostats also require periodic adjustment based on accurate thermometer readings taken in the immediate proximity of the animal.

Emergency Warning

Animals housed in a high-density, mechanically controlled environment are subject to considerable risk of heat prostration if a failure of power or ventilation equipment occurs. To reduce this danger, an alarm and an automatic standby electric generator are highly recommended. Many alarms detect failure of the ventilation. These alarms range from inexpensive power-off alarms to ones that sense temperature extremes and certain gases. Automatic telephone-dialing systems are effective as alarms and are relatively inexpensive. Building designs that allow some side wall panels (e.g., 25% of wall area) to be removed for emergency situations are also recommended.

RECOMMENDED PRACTICES BY SPECIES

Mature animals readily adapt to a broad range of temperatures, but efficiency of production varies. Younger animals are more temperature sensitive. Figure 6 illustrates animal production response to temperature.

Relative humidity has not been shown to influence animal performance, except when accompanied by thermal stress. Relative humidity consistently below 40% may contribute to excessive dustiness; above 80%, it may increase building and equipment deterioration. Disease pathogens also appear to be more viable at either low or high humidity. Relative humidity has a major influence on the effectiveness of skin-wetting cooling methods.

Dairy Cattle

Dairy cattle shelters include confinement stall barns, free stalls, and loose housing. In a stall barn, cattle are usually confined to stalls approximately 4 ft wide, where all chores, including milking and feeding, are conducted. Such a structure requires environmental modification, primarily through ventilation. Total space requirements are 50 to 75 ft^2 per cow. In free-stall housing, cattle are not confined to stalls but can move freely. Space requirements per cow are 75 to 100 ft^2. In loose housing, cattle are free to move within a fenced lot containing resting and feeding areas. Space required in sheltered loose housing is similar to that in free-stall

housing. Shelters for resting and feeding areas are generally open-sided and require no air conditioning or mechanical ventilation, but supplemental air mixing is often beneficial during warm weather. The milking area is in a separate area or facility and may be fully or partially enclosed, thus requiring some ventilation.

For dairy cattle, climate requirements for minimal economic loss are broad, and range from 35 to 75°F with 40 to 80% rh. Below 35°F, production efficiency declines and management problems increase. However, the effect of low temperature on milk production is not as extreme as are high temperatures, where evaporative coolers or other cooling methods may be warranted.

Ventilation Rates for Each 1100 lb Cow

Winter	Spring/Fall	Summer
36 to 47 cfm	142 to 190 cfm	230 to 470 cfm

Required ventilation rates depend on specific thermal characteristics of individual buildings and internal heating load. The relative humidity should be maintained between 50 and 80%.

Both loose housing and stall barns require an additional milk room to cool and hold the milk. Sanitation codes for milk production contain minimum ventilation requirements. The market being supplied should be consulted for all applicable codes. Some state codes require positive-pressure ventilation of milk rooms. Milk rooms are usually ventilated with fans at rates of 4 to 10 ach to satisfy requirements of local milk codes and to remove heat from milk coolers. Most milk codes require ventilation in the passageway (if any) between the milking area and the milk room.

Beef Cattle

Beef cattle ventilation requirements are similar to those of dairy cattle on a unit weight basis. Beef production facilities often provide only shade and wind breaks.

Swine

Swine housing can be grouped into four general classifications:

1. Farrowing pigs, from birth to 30 lb, and sows
2. Nursery pigs, from 30 to 75 lb
3. Growing/finishing pigs, from 75 lb to market weight
4. Breeding and gestation

In farrowing barns, two environments must be provided: one for sows and one for piglets. Because each requires a different temperature, zone heating and/or cooling is used. The environment within the nursery is similar to that within the farrowing barn for piglets. The requirements for growing barns and breeding stock housing are similar.

Currently recommended practices for **farrowing houses**:

- Temperature: 50 to 68°F, with small areas for piglets warmed to 82 to 90°F by brooders, heat lamps, or floor heat. Avoid cold drafts and extreme temperatures. Hovers are sometimes used. Provide supplemental cooling for sows (usually drippers or zone cooling) in extreme heat.
- Relative humidity: Up to 70% maximum
- Ventilation rate: 20 to 500 cfm per sow and litter (about 400 lb total weight). The low rate is for winter; the high rate is for summer temperature control.
- Space: 35 ft^2 per sow and litter (stall); 65 ft^2 per sow and litter (pens)

Recommendations for **nursery barns**:

- Temperature:
  80°F for first week after weaning. Lower room temperature 3°F per week to 72°F. Provide warm, draft-free floors. Provide supplemental cooling for extreme heat (temperatures 85°F and above).
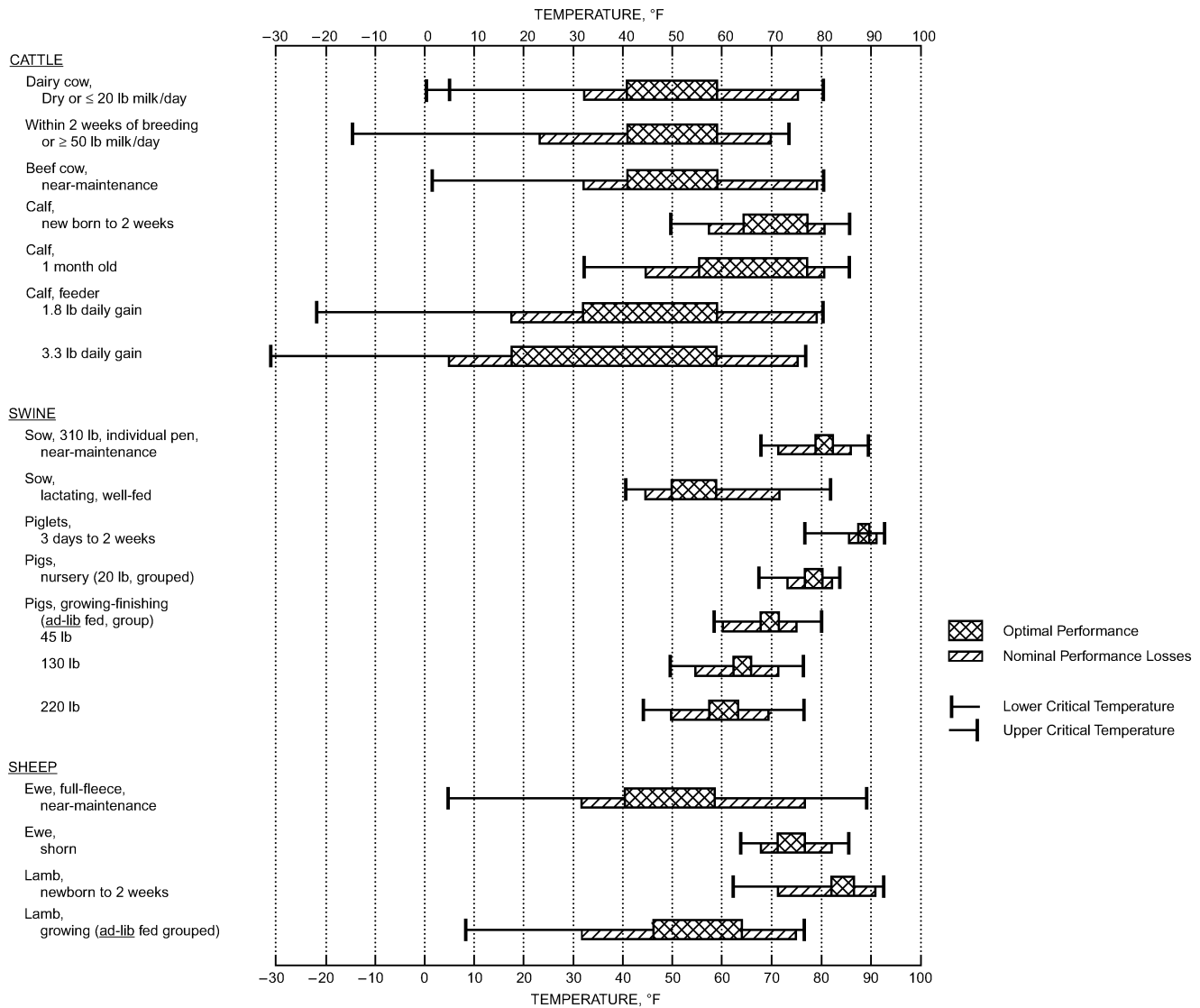
Fig. 6   Critical Ambient Temperatures and Temperature Zone for Optimum Performance and Nominal Performance Loss in Farm Animals
(Adapted from Hahn 1985, in *Stress Physiology in Livestock*, Vol. II, CRC Press)

- Ventilation rate:
  2 to 2.5 cfm per pig, 12 to 30 lb each
  3 to 35 cfm per pig, 30 to 75 lb each
- Space:
  2 to 2.5 ft^2 per pig, 12 to 30 lb each
  3 to 4 ft^2 per pig, 30 to 75 lb each

  Recommendations for **growing** and **gestation barns**:

- Temperature:
  55 to 72°F preferred. Provide supplemental cooling (sprinklers or evaporative coolers) for extreme heat.
- Relative humidity:
  75% maximum in winter; no established limit in summer
- Ventilation rate:
  Growing pig (75 to 150 lb), 7 to 75 cfm
  Finishing pig (150 to 220 lb), 10 to 120 cfm
  Gestating sow (325 lb), 12 to 150 cfm
  Boar/breeding sow (400 lb), 14 to 300 cfm

- Space:
  6 ft^2 per pig, 75 to 150 lb each
  8 ft^2 per pig, 150 to 220 lb each
  14 to 24 ft^2 per sow, 240 to 500 lb each

Poultry

In broiler and brooder houses, growing chicks require changing environmental conditions, and heat and moisture dissipation rates increase as the chicks grow older. Supplemental heat, usually from brooders, is used until sensible heat produced by the birds is adequate to maintain an acceptable air temperature. At early stages of growth, moisture dissipation per bird is low. Consequently, low ventilation rates are recommended to prevent excessive heat loss. Litter is allowed to accumulate over 3 to 5 flock placements. Lack of low-cost litter material may justify the use of concrete floors. After each flock, caked litter is removed and fresh litter is added.

Housing for poultry may be open, curtain-sided or totally enclosed. Mechanical ventilation depends on the type of housing

used. For open-sided housing, ventilation is generally natural airflow in warm weather, supplemented with stirring fans, and by fans with closed curtains in cold weather or during the brooding period. Mechanical ventilation is used in totally enclosed housing. Newer houses have smaller curtains and well-insulated construction to accommodate both natural and mechanical ventilation operation.

Recommendations for **broiler houses**:

- Room temperature: 60 to 80°F
- Temperature under brooder hover: 86 to 91°F, reducing 5°F per week until room temperature is reached
- Relative humidity: 50 to 80%
- Ventilation rate: Sufficient to maintain house within 2 to 4°F of outside air conditions during summer. Generally, rates are about 0.1 cfm per lb live weight during winter and 1 to 2 cfm per lb for summer conditions.
- Space: 0.6 to 1.0 ft^2 per bird (for the first 21 days of brooding, only 50% of floor space is used)
- Light: Minimum of 10 lx or 1 footcandle to 28 days of age; 1 to 20 lx or 0.1 to 2 footcandles for growout (in enclosed housing).

Recommendations for **breeder houses** with birds on litter and slatted floors:

- Temperature: 50 to 86°F maximum; consider evaporative cooling if higher temperatures are expected.
- Relative humidity: 50 to 75%
- Ventilation rate: Same as for broilers on live weight basis.
- Space: 2 to 3 ft^2 per bird

Recommendations for **laying houses** with birds in cages:

- Temperature, relative humidity, and ventilation rate: Same as for breeders.
- Space: 50 to 65 in^2 per hen minimum
- Light: Controlled day length using light-controlled housing is generally practiced (January through June).

Laboratory Animals

The well-being and experimental response of laboratory animals depend greatly on the design of the facilities. Cage type, noise levels, light levels, air quality, and thermal environment can affect animal well-being and, in many cases, affect how the animal responds to experimental treatments (Clough 1982; Lindsey et al. 1978; McPherson 1975; Moreland 1975). If any of these factors vary across treatments or even within treatments, it can affect the validity of experimental results, or at least increase experimental error. Consequently, laboratory animal facilities must be designed and maintained to expose the animals to appropriate levels of these environmental conditions and to ensure that all animals in an experiment are in a uniform environment. See Chapter 14 for additional information on laboratory animal facilities.

In the United States, recommended environmental conditions within laboratory animal facilities are usually dictated by the *Guide for the Care and Use of Laboratory Animals* (ILAR 1996). Temperature recommendations vary from 61 to 84°F, depending on the species being housed. The acceptable range for relative humidity is 30 to 70%. For animals in confined spaces, daily temperature fluctuations should be minimized. Relative humidity must also be controlled, but not as precisely as temperature.

Ventilation recommendations are based on room air changes; however, cage ventilation rates may be inadequate in some cages and excessive in other cages, depending on cage and facility design. ILAR (1996) recommendations for room ventilation rates of 10 to 15 ach are an attempt to provide adequate ventilation for the room and cages. This recommendation is based on the assumption that adequate ventilation in the macroenvironment (room) provides sufficient ventilation to the microenvironment (cage). This may be a reasonable assumption when cages have a top of wire rods or mesh. However, several studies have shown that covering cages with filter tops, which provide a protective barrier for rodents and reduce airborne infections and diseases, especially neonatal diarrhea, can create significant differences in microenvironmental conditions.

Maghirang et al. (1995) and Riskowski et al. (1996) surveyed room and cage environmental conditions in several laboratory animal facilities and found that the animal's environmental needs may not be met even though the facilities were designed and operated according to ILAR (1996). The microenvironments were often considerably poorer than the room conditions, especially in microisolator cages. For example, ammonia levels in cages were up to 60 ppm even though no ammonia was detected in a room. Cage temperatures were up to 7°F higher than room temperature and relative humidities up to 41% higher.

Furthermore, cage microenvironments in the same room were found to have significant variation (Riskowski et al. 1996): ammonia levels varied from 0 to 60 ppm, air temperature varied from 1 to 7°F higher than room temperature, relative humidity varied from 1 to 30% higher than room humidity, and average light levels varied from 2 to 337 lx. This survey found three identical rooms that had room ventilation rates from 4.4 to 12.5 ach but had no differences in room or cage environmental parameters.

A survey of laboratory animal environmental conditions in seven laboratory rat rooms was conducted by Zhang et al. (1992). They found that room air ammonia levels were under 0.5 ppm for all rooms, even though room airflow varied from 11 to 24 ach. Air exchange rates in the cages varied from less than 0.1 to 2.5 cfm per rat, and ammonia levels ranged from negligible to 60 ppm. Riskowski et al. (1996) measured several environmental parameters in rat shoebox cages in full-scale room mockups with various room and ventilation configurations. Significant variations in cage temperature and ventilation rates within a room were also found. Varying room ventilation rate from 5 to 15 ach did not have large effects on cage environmental conditions. These studies verify that designs based only on room air changes do not guarantee desired conditions in the animal cages.

In order to analyze the ventilation performance of different laboratory animal research facilities, Memarzadeh (1998) used **computational fluid dynamics** (CFD) to undertake computer simulation of over 100 different room configurations. CFD is a three-dimensional mathematical technique used to compute the motion of air, water, or any other gas or liquid. However, all conditions must be correctly specified in the simulation to produce accurate results. Empirical work defined inputs for such parameters as heat dissipation and surface temperature as well as the moisture, CO_2, and NH_3 mass generation rates for mice.

This approach compared favorably with experimentally measured temperatures and gas concentrations in a typical animal research facility. To investigate the relationships between room configuration parameters and the room and cage environments in laboratory animal research facilities, the following parameters were varied:

- Supply air diffuser type and orientation, air temperature, and air moisture content
- Room ventilation rate
- Exhaust location and number
- Room pressurization
- Rack layout and cage density
- Change station location, design, and status
- Leakage between the cage lower and upper moldings
- Room width

Room pressurization, change station design, and room width had little effect on ventilation performance. However, other factors found to affect either the macroenvironment or microenvironment or both led to the following observations:

- Ammonia production depends on relative humidity. Ten days after the last change of bedding, a high-humidity environment

produced ammonia at about three times the rate of cages in a low-humidity environment.

- Acceptable room and cage ammonia concentrations after 5 days without changing cage bedding are produced by room supply airflow rates of around 0.85 cfm per 100 g of body mass of mice. This is equivalent to 5 ach for the room with single-density racks considered in this study, and 10 ach for the room with double-density racks. The temperature of the supply air must be set appropriately for the heat load in the room. The room with single-density racks contained 1050 mice with a total mass of 21 kg and the room with double-density racks contained 2100 mice with a total mass of 42 kg.

- Increasing the room ventilation rate does not have a large effect on the cage ventilation. Increasing the supply airflow from 5 to 20 ach around single-density racks parallel to the walls reduces the CO_2 concentration from 1764 to 1667 ppm, a reduction of only 6%. For the double-density racks perpendicular to the walls, the reduction is larger, but still only from about 2300 to 1800 ppm (around 20%)

- Both the cage and the room ammonia concentrations can be reduced by increasing the supply air temperatures. This reduces the relative humidity for a given constant moisture content in the air, and the lower relative humidity leads to lower ammonia generation. Raising the supply discharge temperature from 66 to 72°F at 15 ach raises the room temperature by 5°F to around 73°F and the cages by 4°F to around 77°F. This can reduce ammonia concentrations by up to 50%.

- Using 72°F as the supply discharge temperature at 5 ach (the lowest flow rate considered) for double-density racks produces a room temperature around 79°F, with cage temperatures only slightly higher. Although this higher temperature provides a more comfortable environment for the mice (Gordon et al. 1997), the high room temperature may be unacceptable to the scientists working in the room.

- Ceiling or high-level exhausts tend to produce lower room temperatures (for a given supply air temperature, all CFD models were designed to have 72°F at the room exhaust) when compared to low-level exhausts. This indicates that low-level exhausts are less efficient at cooling the room.

- Low-level exhausts appear to ventilate the cages slightly better (up to 27% for the radial diffuser; much less for the slot diffuser) than ceiling or high-level exhausts when the cages are placed parallel to the walls, near the exhausts. Ammonia concentration in the cages decreased even further, although this is because of the higher temperatures in the low-level exhaust cases when compared to the ceiling and high-level exhausts. The room concentrations of CO_2 and ammonia do not show that any type of supply or exhaust is significantly better or worse than the other type.

DESIGN FOR PLANT FACILITIES

Greenhouses, plant growth chambers, and other facilities for indoor crop production overcome adverse outdoor environments and provide conditions conducive to economical crop production. The basic requirements of indoor crop production are (1) adequate light; (2) favorable temperatures; (3) favorable air or gas content; (4) protection from insects and disease; and (5) suitable growing media, substrate, and moisture. Because of their lower cost per unit of usable space, greenhouses are preferred over plant growth chambers for protected crop production.

This section covers greenhouses and plant growth facilities, and Chapter 10 of the 2005 *ASHRAE Handbook—Fundamentals* describes the environmental requirements in these facilities. Figure 7 shows the structural shapes of typical commercial greenhouses. Other greenhouses may have Gothic arches, curved glazing, or simple lean-to shapes. Glazing, in addition to traditional glass, now includes both film and rigid plastics. High light transmission by the
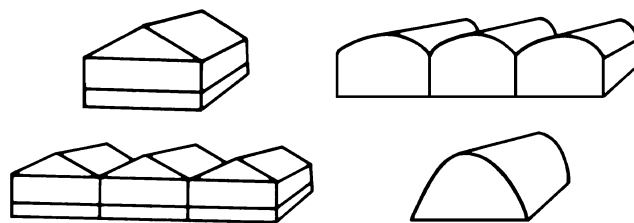
Fig. 7   Structural Shapes of Commercial Greenhouses

glazing is usually important; good location and orientation of the house are important in providing desired light conditions. Location also affects heating and labor costs, exposure to plant disease and air pollution, and material handling requirements. As a general rule in the northern hemisphere, a greenhouse should be placed at a distance of at least 2.5 times the height of the object closest to it in the eastern, western, and southern directions.

GREENHOUSES

Site Selection

Sunlight. Sunlight provides energy for plant growth and is often the limiting growth factor in greenhouses of the central and northern areas of North America during the winter. When planning greenhouses that are to be operated year-round, a designer should design for the greatest sunlight exposure during the short days of midwinter. The building site should have an open southern exposure, and if the land slopes, it should slope to the south.

Soil and Drainage. When plants are to be grown in the soil covered by the greenhouse, a growing site with deep, well-drained, fertile soil, preferably sandy loam or silt loam, should be chosen. Even though organic soil amendments can be added to poor soil, fewer problems occur with good natural soil. However, when good soil is not available, growing in artificial media should be considered. The greenhouse should be level, but the site can and often should be sloped and well-drained to reduce salt build-up and insufficient soil aeration. A high water table or a hardpan may produce water-saturated soil, increase greenhouse humidity, promote diseases, and prevent effective use of the greenhouse. If present, these problems can be alleviated by tile drains under and around the greenhouse. Ground beds should be level to prevent water from concentrating in low areas. Slopes within greenhouses also increase temperature and humidity stratification and create additional environmental problems.

Sheltered Areas. Provided they do not shade the greenhouse, surrounding trees act as wind barriers and help prevent winter heat loss. Deciduous trees are less effective than coniferous trees in midwinter, when the heat loss potential is greatest. In areas where snowdrifts occur, windbreaks and snowbreaks should be 100 ft or more from the greenhouse to prevent damage.

Orientation. Generally, in the northern hemisphere, for single-span greenhouses located north of 35° latitude, maximum transmission during winter is attained by an east-west orientation. South of 35° latitude, orientation is not important, provided headhouse structures do not shade the greenhouse. North-south orientation provides more light on an annual basis.

Gutter-connected or ridge-and-furrow greenhouses are oriented preferably with the ridge line north-south regardless of latitude. This orientation allows the shadow pattern caused by the gutter superstructure to move from the west to the east side of the gutter during the day. With an east-west orientation, the shadow pattern would remain north of the gutter, and the shadow would be widest and create the most shade during winter when light levels are already low. Also, the north-south orientation allows rows of tall crops, such as roses and staked tomatoes, to align with the long dimension of the
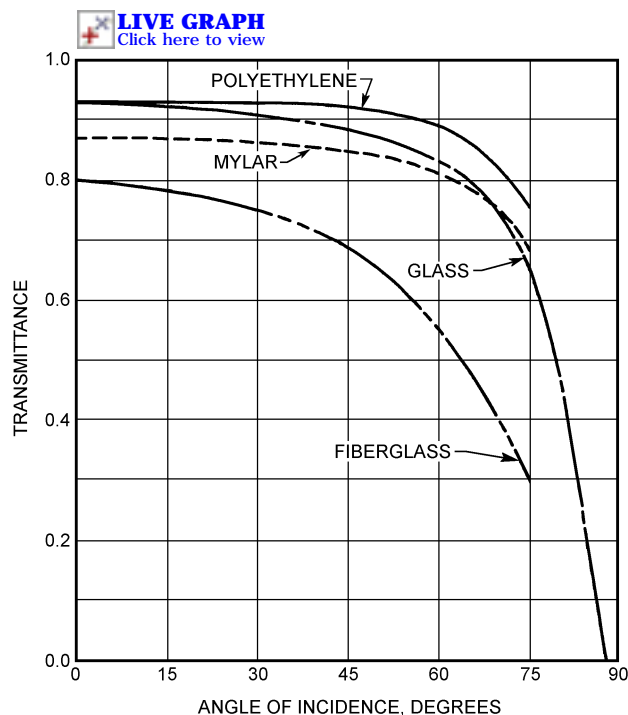
Fig. 8 Transmittance of Solar Radiation Through Glazing Materials for Various Angles of Incidence

house—an alignment that is generally more suitable to long rows and the plant support methods preferred by many growers.

The slope of the greenhouse roof is a critical part of greenhouse design. If the slope is too flat, a greater percentage of sunlight is reflected from the roof surface (Figure 8). A slope with a 1:2 rise-to-run ratio is the usual inclination for a gable roof.

Heating

Structural Heat Loss. Estimates for heating and cooling a greenhouse consider conduction, infiltration, and ventilation energy exchange. In addition, the calculations must consider solar energy load and electrical input, such as light sources, which are usually much greater for greenhouses than for conventional buildings. Generally, conduction q_c plus infiltration q_i are used to determine the peak requirements q_t for heating.

$$q_t = q_c + q_i \tag{4}$$

$$q_c = UA(t_i - t_o) \tag{5}$$

$$q_i = 0.018 VN(t_i - t_o) \tag{6}$$

where

U = overall heat loss coefficient, Btu/h·ft^2·°F (Tables 2 and 3)
A = exposed surface area, ft^2
t_i = inside temperature, °F
t_o = outside temperature, °F
V = greenhouse internal volume, ft^3
N = number of air exchanges per hour (Table 4)

Type of Framing. The type of framing should be considered in determining overall heat loss. Aluminum framing and glazing systems may have the metal exposed to the exterior to a greater or lesser degree, and the heat transmission of this metal is higher than that of the glazing material. To allow for such a condition, the U-factor of the glazing material should be multiplied by the factors shown in Table 3.

Table 2 Suggested Heat Transmission Coefficients

		U, Btu/h·ft^2·°F
Glass		
	Single glazing	1.13
	Double glazing	0.70
	Insulating	Manufacturers' data
Plastic film		
	Single film[a]	1.20
	Double film, inflated	0.70
	Single film over glass	0.85
	Double film over glass	0.60
Corrugated glass fiber		
	Reinforced panels	1.20
Plastic structured sheet[b]		
	16 mm thick	0.58
	8 mm thick	0.65
	6 mm thick	0.72

[a]Infrared barrier polyethylene films reduce heat loss; however, use this coefficient when designing heating systems because the structure could occasionally be covered with non-IR materials.
[b]Plastic structured sheets are double-walled, rigid plastic panels.

Table 3 Construction U-Factor Multipliers

Metal frame and glazing system, 16 to 24 in. spacing	1.08
Metal frame and glazing system, 48 in. spacing	1.05
Fiberglass on metal frame	1.03
Film plastic on metal frame	1.02
Film or fiberglass on wood	1.00

Table 4 Suggested Design Air Changes (N)

New Construction	
Single glass lapped (unsealed)	1.25
Single glass lapped (laps sealed)	1.0
Plastic film covered	0.6 to 1.0
Structured sheet	1.0
Film plastic over glass	0.9
Old Construction	
Good maintenance	1.5
Poor maintenance	2 to 4

Infiltration. Equation (6) may be used to calculate heat loss by infiltration. Table 4 suggests values for air changes N.

Radiation Energy Exchange. Solar gain can be estimated using the procedures outlined in Chapter 30 of the 2005 *ASHRAE Handbook—Fundamentals*. As a guide, when a greenhouse is filled with a mature crop of plants, one-half the incoming solar energy is converted to latent heat, and one-quarter to one-third, to sensible heat. The rest is either reflected out of the greenhouse or absorbed by the plants and used in photosynthesis.

Radiation from a greenhouse to a cold sky is more complex. Glass admits a large portion of solar radiation but does not transmit long-wave thermal radiation in excess of approximately 5000 nm. Plastic films transmit more of the thermal radiation but, in general, the total heat gains and losses are similar to those of glass. Newer plastic films containing infrared (IR) inhibitors reduce the thermal radiation loss. Plastic films and glass with improved radiation reflection are available at a somewhat higher cost. Some research greenhouses use a retractable horizontal heat curtain to reduce the effect of night sky losses. Normally, radiation energy exchange is not considered in calculating the design heat load.

Heating Systems. Greenhouses may have a variety of heaters. One is a convection heater that circulates hot water or steam through plain or finned pipe. The pipe is most commonly placed along walls and occasionally beneath plant benches to create desirable convection currents. A typical temperature distribution pattern created by perimeter heating is shown in Figure 9. More uniform temperatures

can be achieved when about one-third the total heat comes from pipes spaced uniformly across the house. These pipes can be placed above or below the crop, but temperature stratification and shading are avoided when they are placed below. Outdoor weather conditions affect temperature distribution, especially on windy days in loosely constructed greenhouses. Manual or automatic overhead pipes are also used for supplemental heating to prevent snow build-up on the roof. In a gutter-connected greenhouse in a cold climate, a heat pipe should be placed under each gutter to prevent snow accumulation.

An overhead tube heater consists of a unit heater that discharges into 12 to 30 in. diameter plastic film tubing perforated to provide uniform air distribution. The tube is suspended at 6 to 10 ft intervals and extends the length of the greenhouse. Variations include a tube and fan receiving the discharge of several unit heaters. The fan and tube system is used without heat to recirculate the air and, during cold weather, to introduce ventilation air. However, tubes sized for heat distribution may not be large enough for effective ventilation during warm weather.

Perforated tubing, 6 to 10 in. in diameter, placed at ground-level (underbench) heaters can also improve heat distribution. Ideally, the ground-level tubing should draw air from the top of the greenhouse for recirculation or heating. Tubes on or near the floor have the disadvantage of being obstacles to workers and reducing usable floor space.

Underfloor heating can supply up to 25% or more of the peak heating requirements in cold climates. A typical underfloor system uses 0.75 in. plastic pipe spaced 12 to 16 in. on center, and covered with 4 in. of gravel or porous concrete. Hot water, not exceeding 104°F, circulates at a rate of 2 to 2.5 gpm per loop. Pipe loops should generally not exceed 400 ft in length. This can provide 16 to 20 Btu/h·ft^2 from a bare floor, and about 75% as much when potted plants or seedling flats cover most of the floor.

Similar systems can heat soil directly, but root temperature must not exceed 77°F. When used with water from solar collectors or other heat sources, the underfloor area can store heat. This storage consists of a vinyl swimming pool liner placed on top of insulation and a moisture barrier at a depth of 8 to 12 in. below grade, and filled with 50% void gravel. Hot water from solar collectors or other clean sources enters and is pumped out on demand. Some heat sources, such as cooling water from power plants, cannot be used directly but require closed-loop heat transfer to avoid fouling the storage and the power plant cooling water.

Greenhouses can also be bottom-heated with 0.25 in. diameter EPDM tubing (or variations of that method) in a closed loop. The tubes can be placed directly in the growing medium of ground beds or under plant containers on raised benches. The best temperature uniformity is obtained by flow in alternate tubes in opposite directions. This method can supply all the greenhouse heat needed in mild climates.
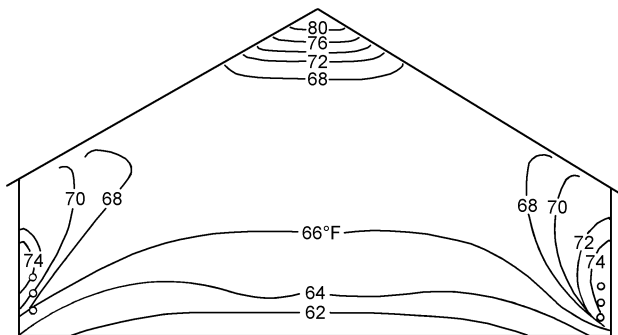
Fig. 9   Temperature Profiles in a Greenhouse Heated with Radiation Piping along the Sidewalls

Bottom heat, underfloor heating, and underbench heating are, because of the location of the heat source, more effective than overhead or peripheral heating, and can reduce energy loss by 20 to 30%.

Unless properly located and aimed, overhead unit heaters, whether hydronic or direct fired, do not give uniform temperature at the plant level and throughout the greenhouse. Horizontal blow heaters positioned so that they establish a horizontal airflow around the outside of the greenhouse offer the best distribution. The airflow pattern can be supplemented with the use of horizontal blow fans or circulators.

When direct combustion heaters are used in the greenhouse, combustion gases must be adequately vented to the outside to minimize danger to plants and humans from products of combustion. One manufacturer recommends that combustion air must have access to the space through a minimum of two permanent openings in the enclosure, one near the bottom. A minimum of 1 in^2 of free area per 1000 Btu/h input rating of the unit, with a minimum of 100 in^2 for each opening, whichever is greater, is recommended. Unvented direct-combustion units should not be used inside the greenhouse.

Many greenhouses combine overhead and perimeter heating. Regardless of the type of heating, it is common practice to calculate overall heat loss first, and then to calculate the individual elements such as the roof, sidewalls, and gables. It is then simple to allocate the overhead portion to the roof loss and the perimeter portions to the sides and gables, respectively.

The annual heat loss can be approximated by calculating the design heat loss and then, in combination with the annual degree-day tables using the 65°F base, estimating an annual heat loss and computing fuel usage on the basis of the rating of the particular fuel used. If a 50°F base is used, it can be prorated.

Heat curtains for energy conservation are becoming more important in greenhouse construction. Although this energy savings may be considered in the annual energy use, it should not be used when calculating design heat load; the practice is to open the heat curtains during snowstorms to facilitate snow melting, thereby nullifying its contribution to the design heat loss value.

Air-to-air and water-to-air heat pumps have been used experimentally on small-scale installations. Their usefulness is especially sensitive to the availability of a low-cost heat source.

Radiant (Infrared) Heating. Radiant heating is used in some limited applications for greenhouse heating. Steel pipes spaced at intervals and heated to a relatively high temperature by special gas heaters serve as the source of radiation. Because the energy is transmitted by radiation from a source of limited size, proper spacing is important to completely cover the heated area. Further, heavy-foliage crops can shade the lower parts of the plants and the soil, thus restricting the radiation from warming the root zone, which is important to plant growth.

Cogenerated Sources of Heat. Greenhouses have been built near or adjacent to power plants to use the heat and electricity generated by the facility. Although this energy may cost very little, an adequate standby energy source must be provided, unless the power supplier can assure that it will supply a reliable, continuous source of energy.

Cooling

Solar radiation is a considerable source of sensible heat gain; even though some of this energy is reflected from the greenhouse, some of it is converted into latent heat as the plants transpire moisture, and some is converted to plant material by photosynthesis. Natural ventilation, mechanical ventilation, shading, and evaporative cooling are common methods used to remove this heat. Mechanical refrigeration is seldom used to air-condition greenhouses because the cooling load and resulting cost is so high.
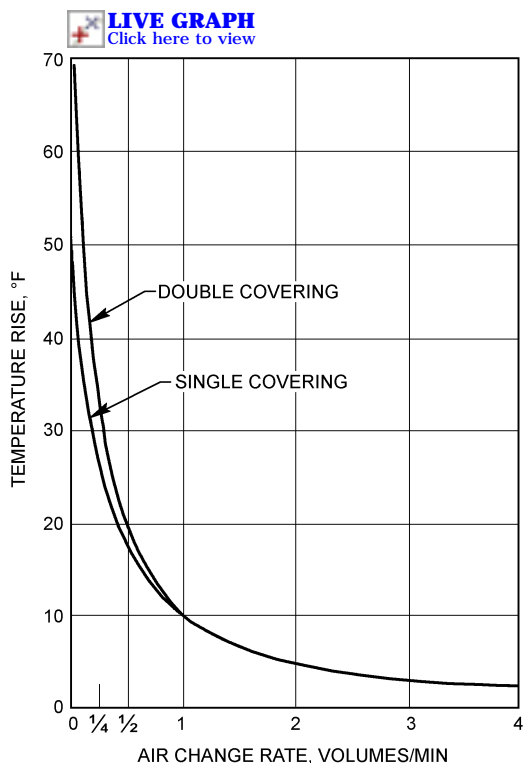
Fig. 10   Influence of Air Exchange Rate on Temperature Rise in Single- and Double-Covered Greenhouses

Table 5   Multipliers for Calculating Airflow for Fan-and-Pad Cooling

Elevation (Above Sea Level)		Max. Interior Light Intensity		Fan-to-Pad Temp. Difference	
ft	F_e	footcandles	F_l	°F	F_t
<1000	1.00	4000	0.80	10	0.70
1000	1.04	4500	0.90	9	0.78
2000	1.08	5000	1.00	8	0.88
3000	1.12	5500	1.10	7	1.00
4000	1.16	6000	1.20	6	1.17
5000	1.20	6500	1.30	5	1.40
6000	1.25	7000	1.40	4	1.75
7000	1.30	7500	1.50		
8000	1.36	8000	1.60		

Table 6   Velocity Factors for Calculating Airflow for Fan-to-Pad Cooling

Fan-to-Pad Distance, ft	F_v	Fan-to-Pad Distance, ft	F_v
20	2.24	65	1.24
25	2.00	70	1.20
30	1.83	75	1.15
35	1.69	80	1.12
40	1.58	85	1.08
45	1.49	90	1.05
50	1.41	95	1.03
55	1.35	100	1.00
60	1.29		

Natural Ventilation. Most older greenhouses and many new ones rely on natural ventilation with continuous roof sashes on each side of the ridge and continuous sashes in the sidewalls. The roof sashes are hinged at the ridge, and the wall sashes are hinged at the top of the sash. During much of the year, vents admit enough ventilating air for cooling without the added cost of running fans.

The principles of natural ventilation are explained in Chapter 27 of the 2005 *ASHRAE Handbook—Fundamentals*. Ventilation air is driven by wind and thermal buoyancy forces. Proper vent openings take advantage of pressure differences created by wind. Thermal buoyancy caused by the temperature difference between the inside and the outside of the greenhouse is enhanced by the area of the vent opening and the stack height (vertical distance between the center of the lower and upper opening). Within the limits of typical construction, the larger the vents, the greater the ventilating air exchanged. For a single greenhouse, the combined area of the sidewall vents should equal that of the roof vents. In ranges of several gutter-connected greenhouses, the sidewall area cannot equal the roof vent area.

Mechanical (Forced) Ventilation. Exhaust fans provide positive ventilation without depending on wind or thermal buoyancy forces. The fans are installed in the side or end walls of the greenhouse and draw air through vents on the opposite side or end walls. Air velocity through the inlets should not exceed 400 fpm.

Air exchange rates between 0.75 and 1 change per minute effectively control the temperature rise in a greenhouse. As shown in Figure 10, the temperature inside the greenhouse rises rapidly at lower airflow rates. At higher airflow rates, the reduction of the temperature rise is small, fan power requirements are increased, and plants may be damaged by the high air speed.

Shading. Shading compounds can be applied in varying amounts to the exterior of the roof of the greenhouse to achieve up to 50% shading. Durability of these compounds varies; ideally, the compound wears away during the summer and leaves the glazing clean in the fall, when shading is no longer needed. In practice, some physical cleaning is needed. Compounds used formerly usually contained lime, which corrodes aluminum and attacks some caulking.

Most compounds used currently are formulated to avoid this problem.

Mechanically operated shade cloth systems with a wide range of shade levels are also available. They are mounted inside the greenhouse to protect them from the weather. Not all shading compounds or shade cloths are compatible with all plastic glazings, so the manufacturers' instructions and precautions should be followed.

Evaporative Cooling.

Fan-and-Pad Systems. Fans for fan-and-pad evaporative cooling are installed in the same manner as fans used for mechanical ventilation. Pads of cellulose material in a honeycomb form are installed on the inlet side. The pads are kept wet continuously when evaporative cooling is needed. As air is drawn through the pads, the water evaporates and cools the air. New pads cool the air by about 80% of the difference between the outdoor dry- and wet-bulb temperatures, or to 3 to 4°F above the wet-bulb temperature. The principles of applying evaporative cooling are explained in Chapter 19 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment* and in Chapter 51 of this volume.

The empirical base rate of airflow is 8 cfm per square foot of floor area. This flow rate is modified by multiplying it by factors for elevation (F_e), maximum interior light intensity (F_l), and allowable temperature rise between the pad and fans (F_t). These factors are listed in Table 5. The overall factor for the house is given by the following equation:

$$F_h = F_e F_l F_t \qquad (7)$$

The maximum fan-to-pad distance should be kept to 175 ft, although some greenhouses with distances of 225 ft have shown no serious reduction in effectiveness. With short distances, the air velocity becomes so low that the air feels clammy and stuffy, even though the airflow is sufficient for cooling. Therefore, a velocity factor F_v listed in Table 6 is used for distances less than 100 ft. For distance less than 100 ft, F_v is compared to F_h. The factor that gives

Table 7 Recommended Air Velocity Through Various Pad Materials

Pad Type and Thickness	Air Face Velocity Through Pad,* fpm
Corrugated cellulose, 4 in. thick	250
Corrugated cellulose, 6 in. thick	350

*Speed may be increased by 25% where construction is limiting.

Table 8 Recommended Water Flow and Sump Capacity for Vertically Mounted Cooling Pad Materials

Pad Type and Thickness	Minimum Water Rate per Linear Foot of Pad, gpm	Minimum Sump Capacity per Unit Pad Area, gal/ft^2
Corrugated cellulose, 4 in. thick	0.5	0.8
Corrugated cellulose, 6 in. thick	0.8	1.0

the greatest airflow is used to modify the empirical base rate. For fan-to-pad distances greater than 100 ft, F_v can be ignored.

For best performance, pads should be installed on the windward side, and fans spaced within 25 ft of each other. Fans should not blow toward pads of an adjacent house unless it is at least 50 ft away. Fans in adjacent houses should be offset if they blow toward each other and are within 15 ft of each other.

Recommended air velocities through commonly used pads are listed in Table 7. Water flow and sump capacities are shown in Table 8. The system should also include a small, continuous bleed-off of water to reduce the build-up of dirt and other impurities.

Unit Evaporative Coolers. This equipment contains the pads, water pump, sump, and fan in one unit. Unit coolers are primarily used for small compartments. They are mounted 15 to 20 ft apart on the sidewall and blow directly into the greenhouse. They cool a distance of up to 50 ft from the unit. A side sash on the outside opposite wall is the best outlet, but roof vents may also work. The roof vent on the same side as the unit should be slightly open for better air distribution. If the roof vent on the opposite side is opened instead, air may flow directly out the vent and not cool the opposite side of the greenhouse.

Fog. In a direct-pressure atomizer, a high-pressure pump forces water at 800 to 1000 psi through a special fog nozzle. Fog is considered to be a water droplet smaller than 40 μm in diameter. The direct-pressure atomizer generates droplets of 35 μm or less. This requires a superior filter to minimize clogging of the very small nozzle orifices.

A line of nozzles placed along the top of the vent opening can cool the entering air nearly to its wet-bulb temperature. Additional lines in the greenhouse continue to cool the air as it absorbs heat in the space.

Fogging cools satisfactorily with less airflow than fan-and-pad systems, but the fan capacity must still be based on one air change per minute to ventilate the greenhouse when the cooler will be used without fog.

Other Environmental Controls

Humidity Control. At various times during the year, humidity may need to be controlled in the greenhouse. When the humidity is too high at night, it can be reduced by adding heat and ventilating simultaneously. When the humidity is too low during the day, it can be increased by turning on a fog or mist nozzle.

Winter Ventilation. During the winter, houses are normally closed tightly to conserve heat, but photosynthesis by the plants may lower the carbon dioxide level to such a point that it slows plant growth. Some ventilation helps maintain inside carbon dioxide levels. A normal rate of airflow for winter ventilation is 2 to 3 cfm per square foot of floor area.

Table 9 Constants to Convert to W/m^2

Light Source	klx	μmol/(s·m^2)
400 to 700 nm		
Incandescent (INC)	3.99	0.20
Fluorescent cool white (FCW)	2.93	0.22
Fluorescent warm white (FWW)	2.81	0.21
Discharge clear mercury (HG)	2.62	0.22
Metal halide (MH)	3.05	0.22
High-pressure sodium (HPS)	2.45	0.20
Low-pressure sodium (LPS)	1.92	0.20
Daylight	4.02	0.22

Air Circulation. Continuous air circulation within the greenhouse reduces still-air conditions that favor plant diseases. Recirculating fans, heaters that blow air horizontally, and fans attached to polyethylene tubes are used to circulate air. The amount of recirculation has not been well defined, except that some studies have shown high air velocities (greater than 200 fpm) can harm plants or reduce growth.

Insect Screening. Insect screening is being used to cover vent inlets and outlets. These fine-mesh screens increase resistance to airflow, which must be considered when selecting ventilation fans. The screen manufacturer should provide static pressure data for its screens. The pressure drop through the screen can be reduced by framing out from the vent opening to increase the area of the screen.

Carbon Dioxide Enrichment. Carbon dioxide is added in some greenhouse operations to increase growth and enhance yields. However, CO_2 enrichment is practical only when little or no ventilation is required for temperature control. Carbon dioxide can be generated from solid CO_2 (dry ice), bottled CO_2, and misting carbonated water. Bulk or bottled CO_2 gas is usually distributed through perforated tubing placed near the plant canopy. Carbon dioxide from dry ice is distributed by passing greenhouse air through an enclosure containing dry ice. Air movement around the plant leaf increases the efficiency with which the plant absorbs whatever CO_2 is available. One study found an air speed of 100 fpm to be equivalent to a 50% enrichment in CO_2 without forced air movement.

Radiant Energy. Light is normally the limiting factor in greenhouse crop production during the winter. North of the 35th parallel (in the northern hemisphere), light levels are especially inadequate or marginal in fall, winter, and early spring. Artificial light sources, usually high-intensity discharge (HID) lamps, may be added to greenhouses to supplement low natural light levels. High-pressure sodium (HPS), metal halide (MH), low-pressure sodium (LPS), and, occasionally, mercury lamps coated with a color-improving phosphor are currently used. Because differing irradiance or illuminance ratios are emitted by the various lamp types, the incident radiation is best described as radiant flux density (W/ft^2) between 400 and 850 nm, or as photon flux density between 400 and 700 nm, rather than in photometric terms of lux or footcandles.

To assist in relating irradiance to more familiar illuminance values, Table 9 shows constants for converting illuminance (lux) and photon flux density [μmol/(s·m^2)] of HPS, MH, LPS, and other lamps to the irradiance (W/m^2). One footcandle is approximately 10 lux.

Table 10 gives values of suggested irradiance at the top of the plant canopy, duration, and time of day for supplementing natural light levels for specific plants.

HID lamps in luminaires developed specifically for greenhouse use are often placed in a horizontal position, which may decrease both the light output and the life of the lamp. These drawbacks may be balanced by improved horizontal and vertical uniformity as compared to industrial parabolic reflectors.

Photoperiod Control. Artificial light sources are also used to lengthen the photoperiod during the short days of winter. Photoperiod control requires much lower light levels than those needed for

Table 10 Suggested Radiant Energy, Duration, and Time of Day for Supplemental Lighting in Greenhouses

Plant and Stage of Growth	W/ft²	Duration Hours	Duration Time
African violets	1 to 2	12 to 16	0600-1800
early-flowering			0600-2200
Ageratum	1 to 4.5	24	
early-flowering			
Begonias—fibrous rooted	1 to 2	24	
branching and early-flowering			
Carnation	1 to 2	16	0800-2400
branching and early-flowering			
Chrysanthemums	1 to 2	16	0800-2400
vegetable growth branching and multiflowering	1 to 2	8	0800-1600
Cineraria	0.6 to 1	24	
seedling growth (four weeks)			
Cucumber	1 to 2	24	
rapid growth and early-flowering			
Eggplant	1 to 4.5	24	
early-fruiting			
Foliage plants	0.6 to 1	24	
(Philodendron, Schefflera) rapid growth			
Geranium	1 to 4.5	24	
branching and early-flowering			
Gloxinia	1 to 4.5	16	0800-2400
early-flowering	0.6 to 1	24	
Lettuce	1 to 4.5	24	
rapid growth			
Marigold	1 to 4.5	24	
early-flowering			
Impatiens—New Guinea	1	16	0800-2400
branching and early-flowering			
Impatiens—Sultana	1 to 2	24	
branching and early-flowering			
Juniper	1 to 4.5	24	
vegetative growth			
Pepper	1 to 2	24	
early-fruiting, compact growth			
Petunia	1 to 4.5	24	
branching and early-flowering			
Poinsettia—vegetative growth	1	24	
branching and multiflowering	1 to 2	8	0800-1600
Rhododendron	1	16	0800-2400
vegetative growth (shearing tips)			
Roses (hybrid teas, miniatures)	1 to 4.5	24	
early-flowering and rapid regrowth			
Salvia	1 to 4.5	24	
early-flowering			
Snapdragon	1 to 4.5	24	
early-flowering			
Streptocarpus	1	16	0800-2400
early-flowering			
Tomato	1 to 2	16	0800-2400
rapid growth and early-flowering			
Trees (deciduous)	0.6	16	1600-0800
vegetative growth			
Zinnia	1 to 4.5	24	
early-flowering			

photosynthesis and growth. Photoperiod illuminance needs to be only 0.6 to 1.1 W/ft². The incandescent lamp is the most effective light source for this purpose because of its higher far-red component. Lamps such as 150 W (PS-30) silverneck lamps spaced 10 to 13 ft on centers and 13 ft above the plants provide a cost-effective system. Where a 13 ft height is not practical, 60 W extended service lamps on 6.5 ft centers are satisfactory. One method of photoperiod control is to interrupt the dark period by turning the lamps on at 2200 and off at 0200. The 4 h interruption, initially based on chrysanthemum response, induces a satisfactory long-day response in all photoperiodically sensitive species. Many species, however, respond to interruptions of 1 h or less. Demand charges can be reduced in large installations by operating some sections from 2000 to 2400 and others from 2400 to 0400. The biological response to these schedules, however, is much weaker than with the 2200 to 0200 schedule, so some varieties may flower prematurely. If the 4 h interruption period is used, it is not necessary to keep the light on throughout the interruption period. Photoperiod control of most plants can be accomplished by operating the lamps on light and dark cycles with 20% *on* times; for example, 12 s/min. The length of the dark period in the cycle is critical, and the system may fail if the dark period exceeds about 30 min. Demand charges can be reduced by alternate scheduling of the *on* times between houses or benches without reducing the biological effectiveness of the interruption.

Plant displays in places such as showrooms or shopping malls require enough light for plant maintenance and a spectral distribution that best shows the plants. Metal halide lamps, with or without incandescent highlighting, are often used for this purpose. Fluorescent lamps, frequently of the special phosphor plant-growth type, enhance color rendition, but are more difficult to install in aesthetically pleasing designs.

Design Conditions

Plant requirements vary from season to season and during different stages of growth. Even different varieties of the same species of plant may vary in their requirements. State and local cooperative extension offices are a good source of specific information on design conditions affecting plants. These offices also provide current, area-specific information on greenhouse operations.

Alternative Energy Sources and Energy Conservation

Limited progress has been achieved in heating commercial greenhouses with solar energy. Collecting and storing the heat requires a volume at least one-half the volume of the entire greenhouse. Passive solar units work at certain times of the year and, in a few localities, year-round.

If available, reject heat is a possible source of winter heat. Winter energy and solar (photovoltaic) sources are possible future energy sources for greenhouses, but the development of such systems is still in the research stage.

Energy Conservation. A number of energy-saving measures (e.g., thermal curtains, double glazing, and perimeter insulation) have been retrofitted to existing greenhouses and incorporated into new construction. Sound maintenance is necessary to keep heating system efficiency at a maximum level.

Automatic controls, such as thermostats, should be calibrated and cleaned at regular intervals, and heating-ventilation controls should interlock to avoid simultaneous operation. Boilers that can burn more than one type of fuel allow use of the most inexpensive fuel available.

Modifications to Reduce Heat Loss

Film covers that reduce heat loss are used widely in commercial greenhouses, particularly for growing foliage plants and other species that grow under low light levels. Irradiance (intensity) is reduced 10 to 15% per layer of plastic film.

One or two layers of transparent 4 or 6 mil continuous-sheet plastic is stretched over the entire greenhouse (leaving some vents uncovered), or from the ridge to the sidewall ventilation opening. When two layers are used, (outdoor) air at a pressure of 0.2 to 0.25 in. of water is introduced continuously between the layers of film to maintain the air space between them. When a single layer is used, an air space can be established by stretching the plastic over the glazing bars and fastening it around the edges, or a length of polyethylene tubing can be placed between the glass and the plastic and inflated (using outside air) to stretch the plastic sheet.

Double-Glazing Rigid Plastic. Double-wall panels are manufactured from acrylic and polycarbonate plastics, with walls separated by about 0.4 in. Panels are usually 48 in. wide and 96 in. or longer. Nearly all types of plastic panels have a high thermal expansion coefficient and require about 1% expansion space (0.12 in/ft). When a panel is new, light reduction is roughly 10 to 20%. Moisture accumulation between the walls of the panels must be avoided.

Double-Glazing Glass. The framing of most older greenhouses must be modified or replaced to accept double glazing with glass.

Light reduction is 10% more than with single glazing. Moisture and dust accumulation between glazings increases light loss. As with all types of double glazing, snow on the roof melts slowly and increases light loss. Snow may even accumulate enough to cause structural damage, especially in gutter-connected greenhouses.

Silicone Sealants. Transparent silicone sealant in the glass overlaps of conventional greenhouses reduces infiltration and may produce heat savings of 5 to 10% in older structures. There is little change in light transmission.

Precautions. The preceding methods reduce heat loss by reducing conduction and infiltration. They may also cause more condensation, higher relative humidity, lower carbon dioxide concentration, and an increase in ethylene and other pollutants. Combined with the reduced light levels, these factors may cause delayed crop production, elongated plants, soft plants, and various deformities and diseases, all of which reduce the marketable crop.

Thermal Blankets. Thermal blankets are any flexible material that is pulled from gutter to gutter and end to end in a greenhouse, or around and over each bench, at night. Materials ranging from plastic film to heavy cloth, or laminated combinations, have successfully reduced heat losses by 25 to 35% overall. Tightness of fit around edges and other obstructions is more important than the kind of material used. Some films are vaportight and retain moisture and gases. Others are porous and allow some gas exchange between the plants and the air outside the blanket. Opaque materials can control crop day length when short days are part of the requirement for that crop. Condensation may drip onto and collect on the upper sides of some blanket materials to such an extent that they collapse.

Multiple-layer blankets, with two or more layers separated by air spaces, have been developed. One such design combines a porous-material blanket and a transparent film blanket; the latter is used for summer shading. Another design has four layers of porous, aluminum foil-covered cloths, with the layers separated by air.

Thermal blankets may be opened and closed manually as well as automatically. The decision to open or close should be based on irradiance level and whether it is snowing, rather than on time of day. Two difficulties with thermal blankets are the physical problems of installation and use in greenhouses with interior supporting columns, and the loss of space from shading by the blanket when it is not in use during the day.

Other Recommendations. Although the foundation can be insulated, the insulating materials must be protected from moisture, and the foundation wall should be protected from freezing. All or most of the north wall can be insulated with opaque or reflective-surface materials. The insulation reduces the amount of diffuse light

entering the greenhouse and, in cloudy climates, causes reduced crop growth near the north wall.

Ventilation fan cabinets should be insulated, and fans not needed in winter should be sealed against air leaks. Efficient management and operation of existing facilities are the most cost-effective ways to reduce energy use.

PLANT GROWTH ENVIRONMENTAL FACILITIES

Controlled-environment rooms (CERs), also called plant growth chambers, include all controlled or partially controlled environmental facilities for growing plants, except greenhouses. CERs are indoor facilities. Units with floor areas less than 50 ft^2 may be moveable with self-contained or attached refrigeration units. CERs usually have artificial light sources, provide control of temperature and, in some cases, control relative humidity and CO_2 level.

CERs are used to study all aspects of botany. Some growers use growing rooms to increase seedling growth rate, produce more uniform seedlings, and grow specialized, high-value crops. The main components of the CER are (1) an insulated room or an insulated box with an access door; (2) a heating and cooling mechanism with associated air-moving devices and controls; and (3) a lamp module at the top of the insulated box or room. CERs are similar to walk-in cold storage rooms, except for the lighting and larger refrigeration system needed to handle heat produced by the lighting.

Location

The location for a CER must have space for the outside dimensions of the chamber, refrigeration equipment, ballast rack, and control panels. Additional space around the unit is necessary for servicing the various components of the system and, in some cases, for substrate, pots, nutrient solutions, and other paraphernalia associated with plant research. The location requires electricity, water, compressed air, and ventilation and exhaust air systems. For planning purposes, electrical densities of up to 140 W/ft^2 of controlled environment space) are possible, or 95 W/ft^2 of total space housing CERs.

Construction and Materials

Wall insulation should have a thermal conductance of less than 0.026 Btu/h·ft^2·°F. Materials should resist corrosion and moisture. The interior wall covering should be metal, with a high-reflectance white paint, or specular aluminum with a reflectivity of at least 80%. Reflective films or similar materials can be used, but require periodic replacement.

Floors and Drains

Floors that are part of the CER should be corrosion-resistant. Tar or asphalt waterproofing materials and volatile caulking compounds should not be used because they are likely to release phytotoxic gases into the chamber atmosphere. The floor must have a drain to remove spilled water and nutrient solutions. The drains should be trapped and equipped with screens to catch plant and substrate debris.

Plant Benches

Three bench styles for supporting the pots and other plant containers are normally encountered in plant growth chambers: (1) stationary benches; (2) benches or shelves built in sections that are adjustable in height; and (3) plant trucks, carts, or dollies on casters, which are used to move plants between chambers, greenhouses, and darkrooms. The bench supports containers filled with moist sand, soil, or other substrate, and is usually rated for loads of at least 50 lb/ft^2. The bench or truck top should be constructed of nonferrous, perforated metal, wire, or metal mesh to allow free passage of air around the plants and to let excess water drain from the containers to the floor and subsequently to the floor drain.

Normally, benches, shelves, or truck tops are adjustable in height so that small plants can be placed close to the lamps and thus receive a greater amount of light. As the plants grow, the shelf or bench is lowered so that the tops of the plants continue to receive the original radiant flux density.

Control

Environmental chambers require complex controls to provide the following:

- Automatic transfer from heating to cooling with 2°F or less dead zone and adjustable time delay.
- Automatic daily switching of the temperature set point for different day and night temperatures (setback may be as much as 10°F).
- Protection of sensors from radiation. Ideally, the sensors are located in a shielded, aspirated housing, but satisfactory performance can be attained by placing them in the return air duct.
- Control of the daily duration of light and dark periods. Ideally, this control should be programmable to change the light period each day to simulate the natural progression of day length. Photoperiod control, however, is normally accomplished with mechanical time clocks, which must have a control interval of 5 min or less for satisfactory timing.
- Protective control to prevent the chamber temperature from going more than a few degrees above or below the set point. Control should also prevent short-cycling of the refrigeration system, especially when condensers are remotely located.
- Control of the CO_2 level in enriched environment chambers.
- Audible and visual alarms to alert personnel of malfunctions.
- Maintenance of relative humidity to prescribed limits.

Data loggers, recorders, or recording controllers are recommended for monitoring daily operation. Solid-state, microprocessor-based controls are widely used for programming, controlling, and monitoring the CER conditions. Host systems are also used to program and monitor larger numbers of units in a common facility, and most offer remote access functions. Host systems tend to be vendor-specific in their use and application.

Heating, Air Conditioning, and Airflow

When the lights are on, cooling will normally be required, and the heater will rarely be called on to operate. When the lights are off, however, both heating and cooling may be needed. Conventional refrigeration is generally used with some modification. Direct-expansion units usually operate with a hot-gas bypass to prevent numerous on/off cycles, and secondary coolant may use aqueous ethylene glycol rather than chilled water. Heat is usually provided by electric heaters, but other energy sources can be used, including hot gas from the refrigeration.

The plant compartment is the heart of the growth chamber. The primary design objective, therefore, is to provide the most uniform, consistent, and regulated environmental conditions possible. Thus, airflow must be adequate to meet specified psychrometric conditions, but it is limited by the effects of high air speed on plant growth. As a rule, the average air speed in CERs is restricted to about 100 fpm.

To meet the uniform conditions required by a CER, conditioned air is normally moved through the space from bottom to top, although some CERs use top-to-bottom airflow. There is no apparent difference in plant growth between horizontal, upward, or downward airflow when the speed is less than 175 fpm. Regardless of the method, a temperature gradient is certain to exist, and should be kept as small as possible. Uniform airflow is more important than the direction of flow; thus, selection of properly designed diffusers or plenums with perforations is essential for achieving it.

The ducts or false sidewalls that direct air from the evaporator to the growing area should be small, but not so small that the noise increases appreciably more than acceptable building air duct noise.

CER design should include some provision for cleaning the interior of the air ducts.

Air-conditioning equipment for relatively standard chambers provides temperatures that range from 45 to 90°F. Specialized CERs that require temperatures as low as −5°F need low-temperature refrigeration equipment and devices to defrost the evaporator without increasing the growing area temperature. Other chambers that require temperatures as high as 115°F need high-temperature components. The air temperature in the growing area must be controlled with the least possible variation about the set point. Temperature variation about the set point can be held to 0.5°F using solid-state controls, but in older facilities, the variation is 1 to 2°F.

The relative humidity in many CERs is simply an indicator of the existing psychrometric conditions and is usually between 50 and 80%, depending on the temperature. Relative humidity in the chamber can be increased by steam injection, misting, hot-water evaporators, and other conventional humidification methods. Steam injection causes the least temperature disturbance, and sprays or misting cause the greatest disturbance. Complete control of relative humidity requires dehumidification as well as humidification.

A typical humidity control includes a cold evaporator or steam injection to adjust the chamber air dew point. The air is then conditioned to the desired dry-bulb temperature by electric heaters, a hot-gas bypass evaporator, or a temperature-controlled evaporator. A dew point lower than about 40°F cannot be obtained with a cold-plate dehumidifier because of icing. Dew points lower than 40°F usually require a chemical dehumidifier in addition to the cold evaporator.

Lighting Environmental Chambers

The type of light source and number of lamps used in CERs are determined by the desired plant response. Traditionally, cool-white fluorescent plus incandescent lamps that produce 10% of the fluorescent illuminance are used. Nearly all illumination data are based on either cool-white or warm-white fluorescent, plus incandescent lamps. A number of fluorescent lamps have special phosphors hypothesized to be the spectral requirements of the plant. Some of these lamps are used in CERs, but there is little data to suggest that they are superior to cool-white and warm-white lamps. In recent years, high-intensity discharge lamps have been installed in CERs, either to obtain very high radiant flux densities, or to reduce the electrical load while maintaining a light level equal to that produced by the less efficient fluorescent-incandescent systems.

One method to design lighting for biological environments is to base light source output recommendations on photon flux density $\mu mol/(s \cdot m^2)$ between 400 and 700 nm, or, less frequently, as radiant flux density between 400 and 700 nm, or 400 and 850 nm. Rather than basing illuminance measurements on human vision, this allows comparisons between light sources as a function of plant photosynthetic potential. Table 9 shows constants for converting various measurement units to W/m^2. However, instruments that measure the 400 to 850 nm spectral range are generally not available, and some controversy exists about the effectiveness of 400 to 850 nm as compared to the 400 to 700 nm range in photosynthesis. The power conversion of various light sources is listed in Table 11.

The design requirements for plant growth lighting differ greatly from those for vision lighting. Plant growth lighting requires a greater degree of horizontal uniformity and, usually, higher light levels than vision lighting. In addition, plant growth lighting should have as much vertical uniformity as possible (a factor rarely important in vision lighting). Horizontal and vertical uniformity are much easier to attain with linear or broad sources, such as fluorescent lamps, than with point sources, such as HID lamps. Tables 12 and 13 show the type and number of lamps, mounting height, and spacing required to obtain several levels of incident energy. Because the data were taken directly under lamps with no reflecting wall surfaces nearby, the incident energy is perhaps one-half of what the plants

Table 11   Input Power Conversion of Light Sources

Lamp Identification		Total Input Power, W	Radiation (400-700 nm), %	Radiation (400-850 nm), %	Other Radiation, %	Conduction and Convection, %	Ballast Loss, %
Incandescent	INC, 100A	100	7	15	75	10	0
Fluorescent							
Cool white	FCW	46	21	21	32	34	13
Cool white	FCW	225	19	19	34	35	12
Warm white	FWW	46	20	20	32	35	13
Plant growth A	PGA	46	13	13	35	39	13
Plant growth B	PGB	46	15	16	34	37	13
Infrared	FIR	46	2	9	39	39	13
Discharge							
Clear mercury	HG	440	12	13	61	17	9
Mercury deluxe	HG/DX	440	13	14	59	18	9
Metal halide	MH	460	27	30	42	15	13
High-pressure sodium	HPS	470	26	36	36	13	15
Low-pressure sodium	LPS	230	27	31	25	22	22

Note: Conversion efficiency is for lamps without luminaires. Values compiled from manufacturers' data, published information, and unpublished test data by R.W. Thimijan.

Table 12   Approximate Mounting Height and Spacing of Luminaires in Greenhouses

Lamp and Wattage	Irradiation, W/ft^2			
	0.6	1.1	2.2	4.4
	Height and Spacing, in.			
HPS (400 W)	118	90	63	39
LPS (180 W)	94	67	47	31
MH (400 W)	106	79	55	35

would receive if the lamps had been placed in a small chamber with highly reflective walls.

Extended-life incandescents, which have a much longer life, lower lamp replacement requirements. These lamps have lower lumen output, but are nearly equivalent in the red portion of the spectrum. For safety, porcelain lamp holders and heat-resistant lamp wiring should be used. Lamps used for CER lighting include fluorescent lamps (usually 1500 mA), 250, 400, and occasionally 1000 W HPS and MH lamps, 180 W LPS lamps, and various sizes of incandescent lamps. In many installations, the abnormally short life of incandescent lamps is caused by vibration from the lamp loft ventilation or from cooling fans. Increased incandescent lamp life under these conditions can be attained by using lamps constructed with a C9 filament.

Energy-saving lamps have approximately equal or slightly lower irradiance per input watt. Because the irradiance per lamp is lower, there is no advantage to using these lamps, except in tasks that can be accomplished with low light levels. Light output of all lamps declines with use, except perhaps for low-pressure sodium (LPS) lamps, which appear to maintain approximately constant output but require an increase in input power during use.

Fluorescent and metal halide designs should be based on 80% of the initial light level. Most CER lighting systems have difficulty maintaining a relatively constant light level over considerable periods of time. Combinations of MH and HPS lamps compound the problem, because the lumen depreciation of the two light sources is significantly different. Thus, over time, the spectral energy distribution at plant level shifts toward the HPS. Lumen output can be maintained in two ways: (1) individual lamps, or a combination of lamps, can be switched off initially and activated as the lumen output decreases; and (2) the oldest 25 to 33% of the lamps can be replaced periodically. Solid-state dimmer systems are commercially available only for low-wattage fluorescent lamps and for mercury lamps.

To maintain a constant distance from plant to light source, light fixtures in many CERs are mounted on movable, counterbalanced light banks. This design requirement precludes separation of the lamps from the plant chamber.

Large rooms, especially those constructed as an integral part of the building and retrofitted as CERs, rarely separate the lamps from the growing area with a transparent barrier. Rooms designed as CERs (at the time a building is constructed) and freestanding rooms or chambers usually separate the lamp from the growing area with a barrier of glass or rigid plastic. Light output from fluorescent lamps is a function of the temperature of the lamp. Thus, the barrier serves a two-fold purpose: (1) to maintain optimum lamp temperature when the growing area temperature is higher or lower than optimum, and (2) to reduce the thermal radiation entering the growing area. Fluorescent lamps should operate in an ambient temperature and airflow environment that maintains the tube wall temperature at 104°F. Under most conditions, the light output of HID lamps is not affected by ambient temperature. The heat must be removed, however, to prevent high thermal radiation from causing adverse biological effects (Figure 11).

Transparent glass barriers remove nearly all radiation from about 350 to 2500 nm. Rigid plastic is less effective than glass; however, the lighter weight and lower breakage risk of plastic makes it a popular barrier material. Ultraviolet is also screened by both glass and plastic (more by plastic). Special UV-transmitting plastic (which degrades rapidly) can be obtained if the biological process requires UV light. When irradiance is very high, especially from HID lamps or large numbers of incandescent lamps or both, rigid plastic can soften from the heat and fall from the supports. Furthermore, very high irradiance and the resulting high temperatures can darken plastic, which can increase the absorptivity and temperature enough to destroy it. Under these conditions, heat-resistant glass may be necessary. The lamp compartment and barrier absolutely require positive ventilation regardless of the light source, and the lamp loft should have limit switches to shut down the lamps if the temperature rises to a critical level.

Phytotrons

A phytotron is a botanical laboratory comprising a series of chambers reproducing any condition of temperature, humidity, illumination, or other plant growth factor. They are typically found in plant-based research buildings. These facilities require substantial electrical and mechanical systems to generate light required for plant growth as well as to remove heat generated by lights and CER cooling systems.

Electrical Requirements. If the exact number and size of units is unknown, an electrical consumption of 0.2 kW/ft^2 may be assumed for lighting input to the CERs. If the CERs have a built-in refrigeration system, the compressor input is typically 80% of lighting input, because the units are designed to maintain the chamber at 50°F with lights on, creating a high latent load on the compressor at

Table 13 Height and Spacing of Luminaires

Light Source	0.03	0.08	0.28	0.84	1.67	2.5	4.6
Fluorescent—Cool White							
40 W single 4 ft lamp, 3.2 klm							
Radiant power, W/m², 400 to 700 nm	0.3	0.9	2.9	8.8			
Illumination, klx	0.10	0.30	1.0	3.0			
Lamps per 100 ft²	1.1	3.3	11	33			
Distance from plants, in.	114	67	36	21			
40 W 2-lamp fixtures (4 ft), 6.4 klm							
Radiant power, W/m², 400 to 700 nm	0.3	0.9	2.9	8.8			
Illumination, klx	0.10	0.30	1.0	3.0			
Fixtures per 100 ft²	0.6	1.7	5.5	16.7			
Distance from plants, in.	161	94	51	30			
215 W 2-8 ft lamps, 31.4 klm							
Radiant power, W/m², 400 to 700 nm	0.3	0.9	2.9	8.8	17.6	23.5	49.0
Illumination, klx	0.10	0.30	1.0	3.0	6.0	8.0	16.7
Lamps per 100 ft²	0.1+	0.4	1.2	3.6	7.1	9.3	20
Distance from plants, in.	346	201	110	63	43	39	28
High-Intensity Discharge							
Mercury-1 400 W parabolic reflector							
Radiant power, W/m², 400 to 700 nm	0.28	0.84	2.80	8.39	16.8	22.4	46.6
Illumination, klx	0.1	0.32	1.1	3.2	6.4	8.6	18.0
Lamps per 100 ft²	0.2	0.5	1.6	4.8	9.3	13.0	27
Distance from plants, in.	299	173	94	55	39	31	24
Metal halide-1 400 W							
Radiant power, W/m², 400 to 700 nm	0.77	0.80	2.68	8.03	16.1	21.4	44.6
Illumination, klx	0.09	0.26	0.88	2.6	5.3	7.0	15.0
Lamps per 100 ft²	0.09	0.2	0.7	2.2	4.4	5.8	12.0
Distance from plants, in.	445	256	142	83	59	51	34
High-pressure sodium 400 W							
Radiant power, W/m², 400 to 700 nm	0.22	0.65	2.18	6.52	13.0	17.4	36.2
Illumination, klx	0.09	0.27	0.89	2.7	5.3	7.1	15.0
Lamps per 100 ft²	0.05	0.14	0.5	1.4	2.8	3.6	7.6
Distance from plants, in.	559	323	177	102	71	63	43
Low-pressure sodium 180 W							
Radiant power, W/m², 400 to 700 nm	0.26	0.79	2.64	7.93	15.9	21.1	44.0
Illumination, klx	0.14	0.41	1.4	4.1	8.3	11.0	23.0
Lamps per 100 ft²	0.08	0.24	0.8	2.4	4.9	6.5	13.6
Distance from plants, in.	421	244	134	9	55	47	33
Incandescent							
Incandescent 100 W							
Radiant power, W/m², 400 to 700 nm	0.14	0.41	1.38	4.14	8.28	11.0	23.0
Illumination, klx	0.033	0.10	0.33	1.0	2.0	2.7	5.6
Lamps per 100 ft²	0.5	1.6	5.2	15.8	32	42	87
Distance from plants, in.	165	94	51	30	21	18	13
Incandescent 150 W flood							
Radiant power, W/m², 400 to 700 nm	0.14	0.41	1.38	4.14	8.28	11.0	23.0
Illumination, klx	0.033	0.098	0.33	1.0	2.0	2.6	5.5
Lamps per 100 ft²	0.3	0.9	3.3	9.3	19.5	26	54
Distance from plants, in.	212	122	67	39	28	24	16
Incandescent-Hg 160 W							
Radiant power, W/m², 400 to 700 nm	0.14	0.41	1.38	4.14	8.28	11.0	23.0
Illumination, klx	0.050	0.15	0.50	1.5	3.0	4.0	8.3
Lamps per 100 ft²	0.7	2.0	6.9	20.4	42	56	111
Distance from plants, in.	146	83	47	26	18	16	11
Sunlight							
Radiant power, W per 100 ft²	2.0	6.2	20.5	61.7	124	164	714
Illumination, klx	0.054	0.16	0.54	1.6	3.2	4.3	8.9

GROWTH CABINET – LIGHTS AIR-COOLED

GROWTH CHAMBER – LIGHTS COOLED
BY REFRIGERATION
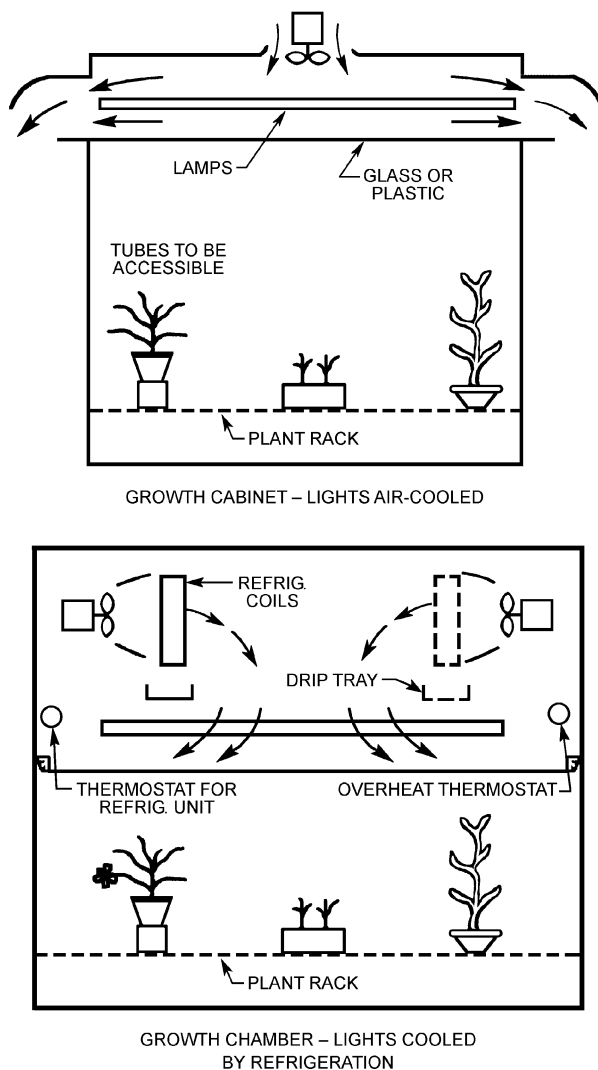
Fig. 11   Cooling Lamps in Growth Chambers

an inefficient operating point. Remote condensing units and remote air-cooled condensers require a separate electrical feed and interconnecting control wiring.

Heat Rejection. Most of the electrical input to the CERs is converted to heat. The heat rejection system must be able to remove that heat from the phytotron; this can be done in a number of ways.

If the CERs are primarily self-contained air-cooled units, the room can be ventilated at a rate that maintains acceptable working conditions in the space (see Chapter 12). Because of the high ventilation rates needed, ensure that air returned to the space is properly filtered to limit the introduction of dust, pollen, insects, and bacteria from outside.

Self-contained CERs with water-cooled condensing units typically use a condenser water loop connected to a cooling tower or fluid cooler to reject heat. Chapter 13 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment* describes selection and design of these systems. Because phytotron facilities operate all year, operation of fluid coolers and cooling towers at ambient temperatures below freezing in cold climates must be considered. Sediment must also be removed from the condenser water, because the condenser on the CER is a relatively low-velocity point in the loop and will plug up with these solids.

Locations of remote condensing units or remote air-cooled condensers should be easily accessible, because they require servicing

at all times of the year. Ensure good airflow around all air-cooled condensers so that discharge air from one unit is not reentrained into adjacent units. Locate equipment away from laboratory exhaust systems that could accelerate corrosion of metal on the units. Refrigerant piping must be carefully designed, sized, and installed to ensure proper oil return and long-term operation of the compressors. Chapter 2 of the 2006 *ASHRAE Handbook—Refrigeration* details these requirements.

Central chilled water can be used for the CERs. The primary consideration is the chilled-water temperature to be provided to each unit. In practice, most CERs operate at internal temperatures between 68 to 77°F when lights are on. As a result, standard chilled-water supply temperatures of 45°F can be used successfully. When lights are off, temperatures of 50°F can be achieved using the same chilled-water temperature. Chambers that require cooler daytime temperatures can use water-cooled condensing units and reject their heat to the chilled-water loop. Some phytotrons use chilled-water supply temperatures of 14°F, but with a high failure rate on the compressors because of low suction temperatures and poor oil return.

Energy Conservation. Because of CERs' very high energy consumption and the predictable day/night cycle of the lighting load, consider balancing the units' schedule to limit electrical demand. Most plants require a 12 to 16 h daily photoperiod. By adjusting the day/night schedule, it is possible to reduce the phytotron's electrical demand by up to 25%.

Chilled-water CERs can have the lowest total energy consumption because of the economy of scale available by using large-capacity chillers versus small compressors. Large laboratory facilities can reject heat from the phytotron to preheat laboratory makeup air. In cold climates, chilled water can be produced without mechanical cooling at ambient temperatures below 28°F. If exposing chilled water to ambient air that could be below freezing, use an appropriate concentration of suitable antifreeze.

Condenser water can also be used to preheat fresh air or, because of its higher temperature, other process loads, such as domestic hot water.

Operating Considerations. CERs with self-contained compressors generate noise. When a large number of units are placed in a room, consideration should be given to attenuating this sound. Chilled-water and remote-condensing-unit CERs provide the quietest environment for workers, because the compressors are remotely located. The total installed cost of these systems may be higher because of the extra cost to remotely locate and energize the cooling systems.

Plants require CO_2 to grow. Many CERs in phytotrons have a central exhaust system to exhaust any chemicals used inside the chambers and to pull in a constant supply of air. Because the units are under a slight negative pressure, makeup air entering the unit must be filtered to limit uncontrolled spread of pollen, insect pests, and bacteria. The flow rate from units depends on the type of crop being grown. A normal rate of ventilation is 2 to 3 cfm per square foot of plant growth area.

Water is required for humidification, plant watering, and cleaning. This often means that three totally separate systems are used. High-purity water is often available in laboratory buildings, and can be used to directly humidify the chambers without introducing waterborne minerals into the chamber. Water for plants should be tempered to avoid root shock. A tempered-water loop with provision for introducing chemical fertilizer, supplied to designated hose stations in the phytotron, is common in larger installations, but normal municipal water supplies are all that is required. Cleaning of these areas is important.

CERs require drainage of cooling coil condensate and plant overwatering. It is important to provide good drainage near the units without excess use of drain lines running exposed across the floor. Similarly, any piping or ducts that operate below the room design dew-point temperature should be insulated to prevent condensation

Table 14   Mounting Height for Luminaires in Storage Areas

	Survival = 0.3 W/ft²		Maintenance = 0.8 W/ft²	
	Distance, ft	lux	Distance, ft	lux
Fluorescent (F)				
FCW two 40 W	3.0	1000	2.5	3000
FWW	3.0	1000	2.5	3000
FCW two 215 W	9.2	1000	5.2	3000
Discharge (HID)				
MH 400 W	10.8	800	6.6	2400
HPS 400 W	14.8	800	8.2	2400
LPS 180 W	11.2	1300	3.9	4000
Incandescent (INC)				
INC 160 W	4.3	350	1.0	1000
INC-HG 160 W	3.9	500	5.2	1500
DL	—	500	—	1500

on those lines. These puddles of water are prime breeding grounds for plant pests, and could cause slip hazards for staff.

Keeping the phytotron clean is important for plants' health. Phytotrons typically have separate potting areas and harvest rooms, both of which generate a lot of dust and dirt. Potting areas must remain sanitary to minimize contamination of seedlings and plantlets. In harvest rooms, mature plants may host insects that can damage young plants. Ventilation systems should keep harvest rooms at negative pressure relative to the cleaner potting areas and phytotron.

Genetically modified plants must be autoclaved once the plant is harvested. Provision should be made for an autoclave next to the harvest room, with a supply of steam or electricity. Odors and steam from the autoclave should be exhausted out of the building.

OTHER PLANT ENVIRONMENTAL FACILITIES

Plants may be held or processed in warehouse-type structures prior to sale or use in interior landscaping. Required temperatures range from slightly above freezing for cold storage of root stock and cut flowers, to 68 to 77°F for maintaining growing plants, usually in pots or containers. Provision must be made for venting fresh air to avoid CO_2 depletion.

Light duration must be controlled by a time clock. When they are in use, lamps and ballasts produce almost all the heat required in an insulated building. Ventilation and cooling may be required. Illumination levels depend on plant requirements. Table 14 shows approximate mounting heights for two levels of illumination. Luminaires mounted on chains permit lamp height to be adjusted to compensate for varying plant height.

The main concerns for interior landscape lighting are how it renders the color of plants, people, and furnishings, as well as how it meets the minimum irradiation requirements of plants. The temperature required for human occupancy is normally acceptable for plants. Light level and duration determine the types of plants that can be grown or maintained. Plants grow when exposed to higher levels, but do not survive below the suggested minimum. Plants may be grouped into three levels based on the following of irradiances:

Low (survival): A minimum light level of 0.07 W/ft² and a preferred level of 0.3 W/ft² irradiance for 8 to 12 h daily.

Medium (maintenance): A minimum of 0.3 W/ft² and a preferred level of 0.8 W/ft² irradiance for 8 to 12 h daily.

High (propagation): A minimum of 0.8 W/ft² and a preferred level of 2.2 W/ft² irradiance for 8 to 12 h daily.

Fluorescent (warm-white), metal halide, or incandescent lighting is usually chosen for public places. Table 13 lists the irradiance of various light sources.

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CHAPTER 23

DRYING AND STORING SELECTED FARM CROPS

CONTROL of moisture content and temperature during storage is critical to preserving the nutritional and economic value of farm crops as they move from the field to the market. Fungi (mold) and insects feed on poorly stored crops and reduce crop quality. Relative humidity and temperature affect mold and insect growth, which is reduced to a minimum if the crop is kept cooler than 50°F and if the relative humidity of the air in equilibrium with the stored crop is less than 60%.

Mold growth and spoilage are a function of elapsed storage time, temperature, and moisture content above critical values. Approximate allowable storage life for cereal grains is shown in Table 1. For example, corn at 60°F and 20% wet basis (w.b.) moisture has a storage life of about 25 days. If it is dried to 18% w.b. after 12 days, half of its storage life has elapsed. Thus, the remaining storage life at 60°F and 18% w.b. moisture content is 25 days, not 50 days.

Insects thrive in stored grain if the moisture content and temperature are not properly controlled. At low moisture contents and temperatures below 50°F, insects remain dormant or die.

Most farm crops must be dried to, and maintained at, a suitable moisture content. For most grains, a suitable moisture content is in the range of 12 to 15% w.b., depending on the specific crop, storage temperature, and length of storage. Oilseeds such as peanuts, sunflower seeds, and flaxseeds must be dried to a moisture content of 8 to 9% w.b. Grain stored for more than a year, grain that is damaged, and seed stock should be dried to a lower moisture content. Moisture levels above these critical values lead to the growth of fungi, which may produce toxic compounds such as aflatoxin.

The maximum yield of dry matter can be obtained by harvesting when the corn has dried in the field to an average moisture content of 26% w.b. However, for quality-conscious markets, the minimum damage occurs when corn is harvested at 21 to 22% w.b. Wheat can be harvested when it has dried to 20% w.b., but harvesting at these moisture contents requires expensive mechanical drying. Although field drying requires less expense than operating drying equipment, total cost may be greater because field losses generally increase as the moisture content decreases.

The price of grain to be sold through commercial market channels is based on a specified moisture content, with price discounts for moisture levels above the specified amount. These discounts compensate for the weight of excess water, cover the cost of water removal, and control the supply of wet grain delivered to market. Grain dried to below the base moisture content set by the market (15.0% w.b. for corn, 13.0% w.b. for soybeans, and 13.5% w.b. for wheat) is not generally sold at a premium; thus, the seller loses the opportunity to sell water for the price of grain.

The preparation of this chapter is assigned to TC 2.2, Plant and Animal Environment.

Grain Quantity

The **bushel** is the common measure used for marketing grain in the United States. Most dryers are rated in bushels per hour for a specified moisture content reduction. The use of the bushel as a measure causes considerable confusion. A bushel is a volume measure equal to 1.244 ft^3. The bushel is used as a volume measure to estimate the holding capacity of bins, dryers, and other containers.

For buying and selling grain, for reporting production and consumption data, and for most other uses, the bushel weight is used. For example, the legal weight of a bushel is 56 lb for corn and 60 lb for wheat. When grain is marketed, bushels are computed as the load weight divided by the bushel weight. So, 56,000 lb of corn (regardless of moisture content) is 1000 bushels. Rice, grain sorghum, and sunflower are more commonly traded on the basis of the hundredweight (100 lb), a measure that does not connote volume. The relationship between bushel by volume and market bushel is the **bulk density** (listed for some crops in Table 2). For some crops, the market has defined a test weight parameter, lb/bu. Test weight is essentially the bulk density, with bushels and cubic feet related by the definition of 1 bushel = 1.244 cubic feet.

The terms **wet bushel** and **dry bushel** sometimes refer to the mass of grain before and after drying. For example, 56,000 lb of 25% moisture corn may be referred to as 1000 wet bushels or simply 1000 bushels. When the corn is dried to 15.5% moisture content (m.c.), only 49,704 lb or 49,704/56 = 888 bushels remain. Thus, a dryer rated on the basis of wet bushels (25% m.c.) shows a capacity 12.6% higher than if rated on the basis of dry bushels (15.5% m.c.).

Table 1 Approximate Allowable Storage Time (Days) for Cereal Grains

Moisture Content, % w.b.[a]	Temperature, °F					
	30	40	50	60	70	80
14	*	*	*	*	200	140
15	*	*	*	240	125	70
16	*	*	230	120	70	40
17	*	280	130	75	45	20
18	*	200	90	50	30	15
19	*	140	70	35	20	10
20	*	90	50	25	14	7
22	190	60	30	15	8	3
24	130	40	15	10	6	2
26	90	35	12	8	5	2
28	70	30	10	7	4	2
30	60	25	5	5	3	1

Based on composite of 0.5% maximum dry matter loss calculated on the basis of USDA research; *Transactions of ASAE* 333-337, 1972; and "Unheated Air Drying," Manitoba Agriculture Agdex 732-1, rev. 1986.

[a]Grain moisture content calculated as percent wet basis: (weight of water in a given amount of wet grain ÷ weight of the wet grain) × 100.

*Approximate allowable storage time exceeds 300 days.

Table 2   Calculated Densities of Grains and Seeds Based on U.S. Department of Agriculture Data

	Bulk Density, lb/ft^3
Alfalfa	48.0
Barley	38.4
Beans, dry	48.0
Bluegrass	11.2 to 24.0
Canola	40.2 to 48.2
Clover	48.0
Corn*	
Ear, husked	28.0
Shelled	44.8
Cottonseed	25.6
Oats	25.6
Peanuts, unshelled	
Virginia type	13.6
Runner, Southeastern	16.8
Spanish	19.8
Rice, rough	36.0
Rye	44.8
Sorghum	40.0
Soybeans	48.0
Sudan grass	32.0
Sunflower	
Nonoil	19.3
Oilseed	25.7
Wheat	48.0

*70 lb of husked ears of corn yield 1 bushel, or 56 lb of shelled corn. 70 lb of ears of corn occupy 2 volume bushels (2.5 ft^3).

The percent of weight lost due to water removed may be calculated by the following equation:

$$\text{Moisture shrink, \%} = \frac{M_o - M_f}{100 - M_f} \times 100$$

where

   M_o = original or initial moisture content, wet basis
   M_f = final moisture content, wet basis

Applying the formula to drying a crop from 25% to 15%,

$$\text{Moisture shrink} = \frac{25 - 15}{100 - 15} \times 100 = 11.76\%$$

In this case, the moisture shrink is 11.76%, or an average 1.176% weight reduction for each percentage point of moisture reduction. The moisture shrink varies depending on the final moisture content. For example, the average shrink per point of moisture when drying from 20% to 10% is 1.111.

Economics

Producers generally have the choice of drying their grain on the farm before delivering it to market, or delivering wet grain with a price discount for excess moisture. The expense of drying on the farm includes both fixed and variable costs. Once a dryer is purchased, the costs of depreciation, interest, taxes, and repairs are fixed and minimally affected by volume of crops dried. The costs of labor, fuel, and electricity vary directly with the volume dried. Total drying costs vary widely, depending on the volume dried, the drying equipment, and fuel and equipment prices. Energy consumption depends primarily on dryer type. Generally, the faster the drying speed, the greater the energy consumption (Table 3).

DRYING EQUIPMENT AND PRACTICES

Contemporary crop-drying equipment depends on mass and energy transfer between the drying air and the product to be dried.

Table 3   Estimated Corn Drying Energy Requirement

Dryer Type	Btu/lb of Water Removed
Unheated air	1000 to 1200
Low temperature	1200 to 1500
Batch-in-bin, continuous-flow in-bin	1500 to 2000
High temperature	
Air recirculating	1800 to 2200
Without air recirculating	2000 to 3000
Combination drying, dryeration	1400 to 1800

Note: Includes all energy requirements for fans and heat.

The drying rate is a function of the initial temperature and moisture content of the crop, the air-circulation rate, the entering condition of the circulated air, the length of flow path through the products, and the time elapsed since the beginning of the drying operation. Outdoor air is frequently heated before it is circulated through the product. Heating increases the rate of heat transfer to the product, increases its temperature, and increases the vapor pressure of the product moisture. For more information on crop responses to drying, see Chapter 11 of the 2005 *ASHRAE Handbook—Fundamentals*.

Most crop-drying equipment consists of (1) a fan to move the air through the product, (2) a controlled heater to increase the ambient air temperature to the desired level, and (3) a container to distribute the drying air uniformly through the product. The exhaust air is vented to the atmosphere. Where climate and other factors are favorable, unheated air is used for drying, and the heater is omitted.

Fans

The fan selected for a given drying application should meet the same requirements important in any air-moving application. It must deliver the desired amount of air against the static resistance of the product in the bin or column, the resistance of the delivery system, and the resistance of the air inlet and outlet.

Foreign material in the grain can significantly change the required air pressure in the following ways:

- Foreign particles larger than the grain (straw, plant parts, and larger seeds) reduce airflow resistance. The airflow rate may be increased by 60% or more.
- Foreign particles smaller than the grain (broken grain, dust, and small seeds) increase the airflow resistance. The effect may be dramatic, decreasing the airflow rate by 50% or more.
- The method used to fill the dryer or the agitation or stirring of the grain after it is placed in the dryer can increase pressure requirements by up to 100%. In some grain, high moisture causes less pressure drop than does low moisture.

Vaneaxial fans are normally recommended when static pressures are less than 3 in. of water. Backward-curved centrifugal fans are commonly recommended when static pressures are higher than 4 in. of water column. Low-speed centrifugal fans operating at 1750 rpm perform well up to about 7 in. of water, and high-speed centrifugal fans operating at about 3500 rpm have the ability to develop static pressure up to about 10 in. of water. The in-line centrifugal fan consists of a centrifugal fan impeller mounted in the housing of an axial flow fan. A bell-shaped inlet funnels the air into the impeller. The in-line centrifugal fan operates at about 3450 rpm and has the ability to develop pressures up to 10 in. of water with 7.5 hp or larger fans.

After functional considerations are made, the initial cost of the dryer fan should be taken into account. Drying equipment has a low percentage of annual use in many applications, so the cost of dryer ownership per unit of material dried is sometimes greater than the energy cost of operation. The same considerations apply to other components of the dryer.

Heaters

Most crop dryer heaters are fueled by either natural gas, liquefied petroleum gas, or fuel oil, though some electric heaters are used. Dryers using coal, biomass (such as corn cobs, stubble, or wood), and solar energy have also been built.

Fuel combustion in crop dryers is similar to combustion in domestic and industrial furnaces. Heat is transferred to the drying air either indirectly, by means of a heat exchanger, or directly, by combining the combustion gases with the drying air. Direct combustion heating is generally limited to natural gas or liquefied petroleum (LP) gas heaters. Most grain dryers use direct combustion. Indirect heating is sometimes used in drying products such as hay because of its greater fire hazard.

Controls

In addition to the usual temperature controls for drying air, all heated air units must have safety controls similar to those found on space-heating equipment. These safety controls shut off the fuel in case of flame failure and stop the burner in case of overheating or excessive drying air temperatures. All controls should be set up to operate the machinery safely in the event of power failure.

SHALLOW-LAYER DRYING

Batch Dryers

The batch dryer cycles through the loading, drying, cooling, and unloading of the grain. Fans force hot air through columns (typically 12 in. wide) or layers (2 to 5 ft thick) of grain. Drying time depends on the type of grain and the amount of moisture to be removed. Some dryers circulate and mix the grain to prevent significant moisture content gradients from forming across the column. A circulation rate that is too fast or a poor selection of handling equipment may cause undue damage and loss of market quality. Batch dryers are suitable for farm operations and are often portable.

Continuous-Flow Dryers

This type of self-contained dryer passes a continuous stream of grain through the drying chamber. Some dryers use a second chamber to cool the hot, dry grain prior to storage. Handling and storage equipment must be available at all times to move grain to and from the dryers. These dryers have crossflow, concurrent flow, or counterflow designs.

Crossflow Dryers. A crossflow dryer is a column dryer that moves air perpendicular to the grain movement. These dryers commonly consist of two or more vertical columns surrounding the drying and cooling air plenums. The columns range in thickness from 8 to 16 in. Airflow rates range from 40 to 160 cfm per cubic foot of grain. The thermal efficiency of the drying process increases as column width increases and decreases as airflow rate increases. However, moisture uniformity and drying capacity increase as airflow rate increases and as column width decreases. Dryers are designed to obtain a desirable balance of airflow rate and column width for the expected moisture content levels and drying air temperatures. Performance is evaluated in terms of drying capacity, thermal efficiency, and dried product moisture uniformity.

As with the batch dryer, a moisture gradient forms across the column because the grain nearest the inside of the column is exposed to the driest air during the complete cycle. Several methods minimize the problem of uneven drying.

One method uses turnflow devices that split the grain stream and move the inside half of the column to the outside and the outside half to the inside. Although effective, turnflow devices tend to plug if the grain is trashy. Under these conditions, a scalper/cleaner should be used to clean the grain before it enters the dryer.

Another method is to divide the drying chamber into sections and duct the hot air so that its direction through the grain is reversed in alternate sections. This method produces about the same effect as the turnflow method.

A third method is to divide the drying chamber into sections and reduce the drying air temperature in each section consecutively. This method is the least effective.

Rack-Type Dryers. In this special type of crossflow dryer, grain flows over alternating rows of heated air supply ducts and air exhaust ducts (Figure 1). This action mixes the grain and alternates exposure to relatively hot drying air and air cooled by previous contact with the grain, promoting moisture uniformity and equal exposure of the product to the drying air.

Concurrent-Flow Dryers. In the concurrent-flow dryer, grain and drying air move in the same direction in the drying chamber. The drying chamber is coupled to a counterflow cooling section. Thus, the hottest air is in contact with the wettest grain, allowing the use of higher drying air temperatures (up to 450°F). Rapid evaporative cooling in the wettest grain prevents the grain temperature from reaching excessive levels. Because higher drying air temperatures are used, the energy efficiency is better than that obtained with a conventional crossflow dryer. In the cooling section, the coolest air initially contacts the coolest grain. The combination of drying and cooling chambers results in lower thermal stresses in the grain kernels during drying and cooling and, thus, a higher-quality product.

Counterflow Dryers. The grain and drying air move in opposite directions in the drying chamber of this dryer. Counterflow is common for in-bin dryers. Drying air enters from the bottom of the bin and exits from the top. The wet grain is loaded from overhead, and floor sweep augers can be used to bring the hot, dry grain to a center sump, where it is removed by another auger. The travel of the sweep is normally controlled by moisture- or temperature-sensing elements.

A drying zone exists only in the lower layers of the grain mass and is truncated at its lower edge so that the grain being removed is not overdried. As a part of the counterflow process, the warm, saturated or near-saturated air leaving the drying zone passes through the cool incoming grain. Some energy is used to heat the cool grain, but some moisture may condense on the cool grain if the bed is deep and the initial grain temperature is low.

Reducing Energy Costs

Recirculation. In most commercially available continuous-flow dryers, optional ducting systems recycle some of the exhaust air from the drying and cooling chambers back to the inlet of the drying chamber (Figure 2). Systems vary, but most make it possible to recirculate all of the air from the cooling chamber and from the lower
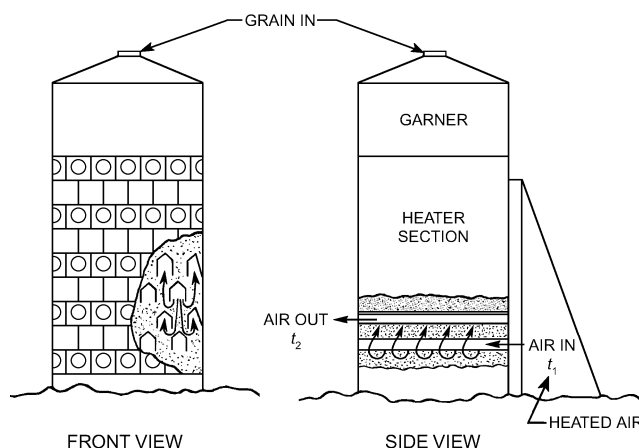
Fig. 1   Rack-Type Continuous-Flow Grain Dryer with Alternate Rows of Air Inlet and Outlet Ducts

two-thirds of the drying chamber. The relative humidity of this recirculated air for most crossflow dryers is less than 50%. Energy savings of up to 30% can be obtained from a well-designed system.

Dryeration. This is another means of reducing energy consumption and improving grain quality. In this process, hot grain with a moisture content one or two percentage points above that desired for storage is removed from the dryer (Figure 3). The hot grain is placed in a dryeration bin, where it tempers without airflow for at least 4 to 6 h. After the first grain delivered to the bin has tempered, the cooling fan is turned on as additional hot grain is delivered to the bin. The air cools the grain and removes 1 to 2% of its moisture before the grain is moved to final storage. If the cooling rate equals the filling rate, cooling is normally completed about 6 h after the last hot grain is added. The crop cooling rate should equal the filling rate of the dryeration bin. A faster cooling rate cools the grain before it has tempered. A slower rate may result in spoilage, since the allowable storage time for hot, damp grain may be only a few days. The required airflow rate is based on dryer capacity and crop density. An airflow rate of 12 cfm for each bushel per hour (bu/h) of dryer capacity provides the cooling capacity to keep up with the dryer when it is drying corn that weighs 56 lb/bu. Recommended airflow rates for some crops are listed in Table 4.

Combination Drying. This method was developed to improve drying thermal efficiency and corn quality. First, a high-temperature

dryer dries the corn to 18 to 20% moisture content. Then it is transferred to a bin, where the full-bin drying system brings the moisture down to a safe storage level.

Dryer Temperature. For energy savings, operating temperatures of batch and continuous-flow dryers are usually set at the highest level that will not damage the product for its end use.

DEEP-BED DRYING

A deep-bed drying system can be installed in any structure that holds grain. Most grain storage structures can be designed or adapted for drying if a means of distributing the drying air uniformly through the grain is provided. A perforated floor (Figure 4) and duct systems placed on the floor of the bin (Figure 5) are the two most common means.

Perforations in the floor should have a total area of at least 10% of the floor area. A perforated floor distributes air more uniformly and offers less resistance to airflow than do ducts, but a duct system is less expensive for larger floor area systems. Ducts can be removed after the grain is removed, and the structure can be cleaned and used for other purposes. Ducts should not be spaced farther apart than one-half times the depth of the grain. The amount of perforated area or the duct length will affect airflow distribution uniformity.

Air ducts and tunnels that disperse air into the grain should be large enough to prevent the air velocity from exceeding 2000 fpm; slower speeds are desirable. Sharp turns, obstructions, or abrupt changes in duct size should be eliminated, as they cause pressure loss. Operating methods for drying grain in storage bins are (1) full-bin
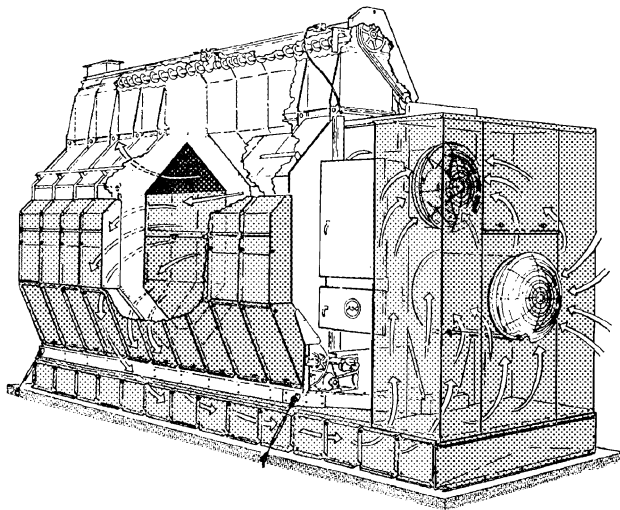
Fig. 2   Crop Dryer Recirculation Unit
(Courtesy Farm Fans, Inc., a division of The GSI Group)

Table 4   Recommended Airflow Rates for Dryeration

Crop	Weight, lb/bu	Recommended Dryeration Airflow Rate, cfm per bu/h
Barley	48	10
Corn	56	12
Durum	60	13
Edible beans	60	13
Flaxseeds	56	12
Millet	50	11
Oats	32	7
Rye	56	12
Sorghum	56	12
Soybeans	60	13
Nonoil sunflower seeds	24	5
Oil sunflower seeds	32	7
Hard red spring wheat	60	13

Note: Basic air volume is 12.9 ft^3/lb.
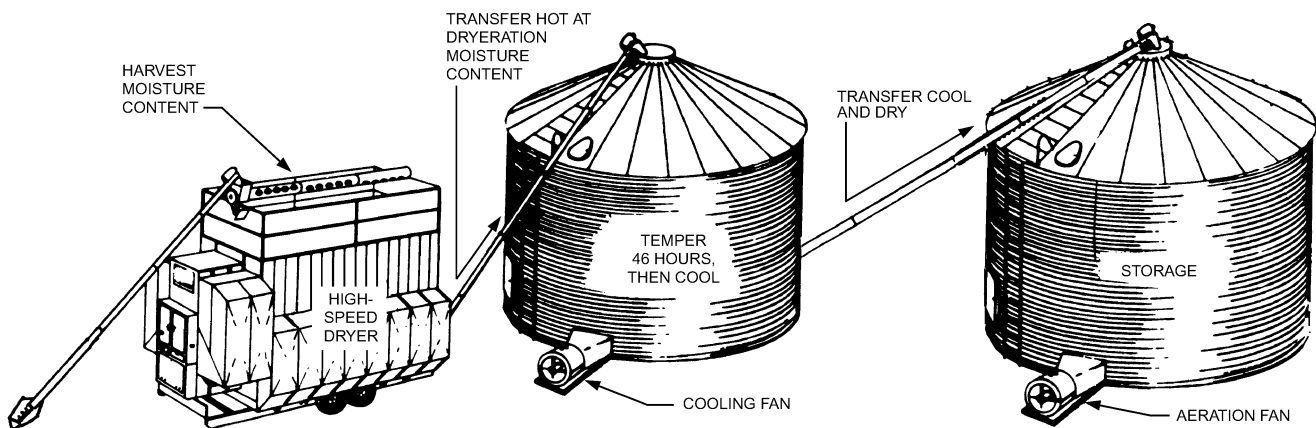
Fig. 3   Dryeration System Schematic
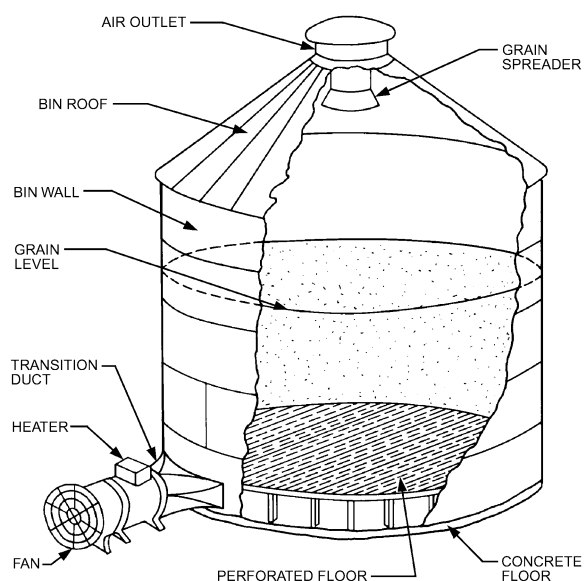
Fig. 4 Perforated Floor System for Bin Drying of Grain
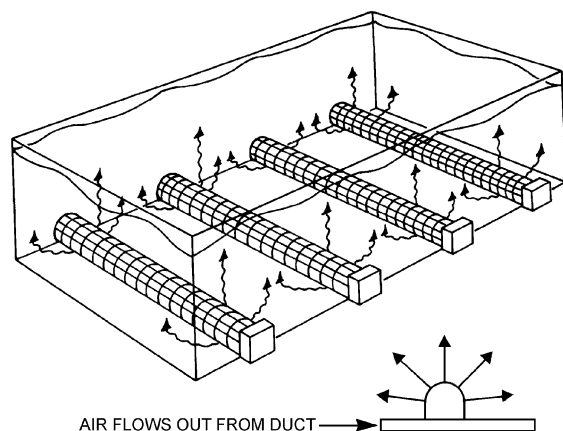
Fig. 5 Tunnel or Duct Air Distribution System

drying, (2) layer drying, (3) batch-in-bin drying, and (4) recirculating/continuous-flow bin drying.

Full-Bin Drying

Full-bin drying is generally performed with unheated air or air heated up to 10°F above ambient. A humidistat is frequently used to sense the humidity of the drying air and turn off the heater if the weather conditions are such that heated air would cause overdrying. A humidistat setting of 55% stops drying at approximately the 12% moisture level for most farm grains, assuming that the ambient relative humidity does not go below this point.

Airflow rate requirements for full-bin drying are generally calculated on the basis of cfm of air required per cubic foot or bushel of grain. The airflow rate recommendations depend on the weather conditions and on the type of grain and its moisture content. Airflow rate is important for successful drying. Because faster drying results from higher airflow rates, the highest economical airflow rate should be used. However, the cost of full-bin drying at high airflow rates may exceed the cost of using column dryers, or the electric power requirement may exceed the available capacity.

Recommendations for full-bin drying with unheated air are shown in Tables 5, 6, and 7. These recommendations apply to the
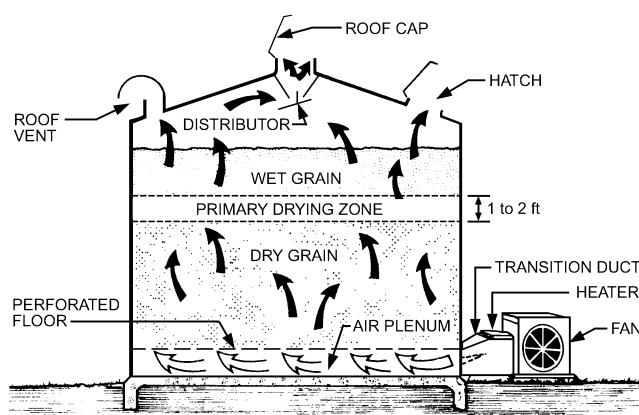
Fig. 6 Three Zones Within Grain During Full-Bin Drying

principal production areas of the continental United States and are based on experience under average conditions; they may not be applicable under unusual weather conditions or even usual weather conditions in the case of late-maturing crops. Full-bin drying may not be feasible in some geographical areas.

The maximum practical depth of grain to be dried (distance of air travel) is limited by the cost of the fan, motor, air distribution system, and power required. This depth seems to be 20 ft for corn and soybeans, and about 15 ft for wheat.

To ensure satisfactory drying, heated air may be used during periods of prolonged fog or rain. Burners should be sized to raise the temperature of the drying air by no more than 10°F above ambient. The temperature should not exceed about 80°F after heating. Overheating the drying air causes the grain to overdry and dry nonuniformly; heat is recommended only to counteract adverse weather conditions. Electric controllers can be applied to fan and heater operation to achieve the final desired grain moisture content.

Drying takes place in a drying zone, which advances upward through the grain (Figure 6). Grain above this drying zone remains at or slightly above the initial moisture content, while grain below the drying zone is at a moisture content in equilibrium with the drying air.

As the direction of air movement does not affect the rate of drying, other factors must be considered in choosing the direction. A pressure system moves the moisture-laden air up through the grain, and it is discharged under the roof. If there are insufficient roof outlets, moisture may condense on the underside of metal roofs. During pressure system ventilation, the wettest grain is near the top surface and is easy to monitor. Fan and motor waste heat enter into the airstream and contribute to drying.

A negative-pressure system moves air down through the grain. Moisture-laden air discharges from the fan to the outside; thus, roof condensation is not a problem. Also, the air picks up some solar heat from the roof. However, the wettest grain is near the bottom of the mass and is difficult to sample. Of the two systems, the pressure system is recommended because it is easier to manage.

The following management practices must be observed to ensure the best performance of the dryer:

1. Minimize foreign material. A scalper-cleaner is recommended for cleaning the grain to reduce air pressure and energy requirements and to help provide uniform airflow for elimination of wet spots.
2. Distribute the remaining foreign material uniformly by installing a grain distributor.
3. Place the grain in layers and keep it leveled.
4. Start the fan as soon as the floor or ducts are covered with grain.
5. Operate the fan continuously with unheated air unless it is raining heavily or there is a dense ground fog. Once all the grain is within 1% of desired storage moisture content, run the fans only when the relative humidity is below 70%.

Table 5   Maximum Corn Moisture Contents, Wet Mass Basis, for Single-Fill Unheated Air Drying

Zone	Full-Bin Airflow Rate, cfm/bu	Harvest Date						
		9-1	9-15	10-1	10-15	11-1	11-15	12-1
		Initial Moisture Content, %						
A	1.0	18	19.5	21	22	24	20	18
	1.25	20	20.5	21.5	23	24.5	20.5	18
	1.5	20	20.5	22.5	23	25	21	18
	2.0	20.5	21	23	24	25.5	21.5	18
	3.0	22	22.5	24	25.5	27	22	18
B	1.0	19	20	20	21	23	20	18
	1.25	19	20	20.5	21.5	24	20.5	18
	1.5	19.5	20.5	21	22.5	24	21	18
	2.0	20	21	22.5	23.5	25	21.5	18
	3.0	21	22.5	23.5	24.5	26	22	18
C	1.0	19	19.5	20	21	22	20	18
	1.25	19	20	20.5	21.5	22.5	20.5	18
	1.5	19.5	20	21	22	23.5	21.5	18
	2.0	20	21	22	23	24.5	21.5	18
	3.0	21	22	23.5	24.5	25.5	22	18
D	1.0	19	19.5	20	21	22	20	18
	1.25	19	19.5	20.5	21	22.5	20.5	18
	1.5	19	19.5	21	22	23	21	18
	2.0	19.5	21	21.5	23	24	21.5	18
	3.0	20.5	21.5	23	24	25	22	18
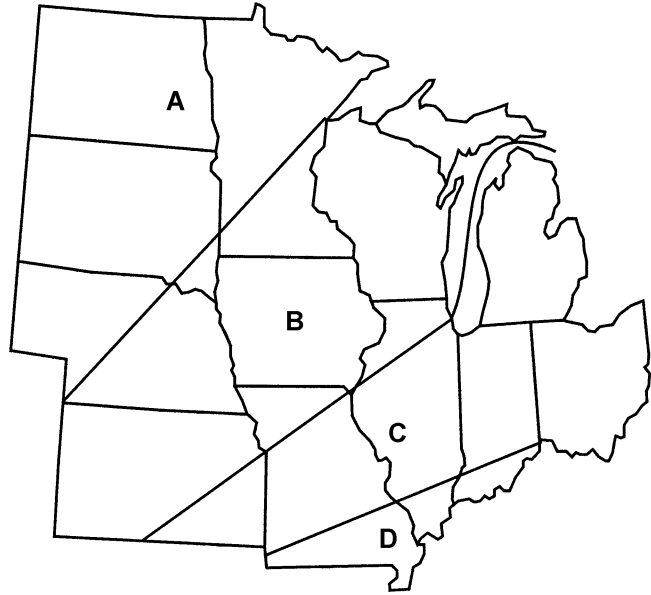
Source: Midwest Plan Service, 1980. Reprinted with permission.

Table 6   Minimum Airflow Rate for Unheated Air Low-Temperature Drying of Small Grains and Sunflower in the Northern Plains of the United States

Airflow Rate		Maximum Initial Moisture Content, % Wet Basis	
cfm/bu	cfm/ft^3	Small Grains	Sunflower
0.5	0.4	16	15
1.0	0.8	18	17
2.0	1.6	20	21

Layer Drying

In layer drying, successive layers of wet grain are placed on top of dry grain. When the top 6 in. has dried to within 1% of the desired moisture content, another layer is added (Figure 7). Compared to full-bin drying, layering reduces the time that the top layers of grain remain wet. Because the effective airflow rate is greater for lower layers, allowable harvest moisture content of grain in these levels can be greater than that in the upper layers. Either unheated air or air heated 10 to 20°F above ambient may be used, but using heated air controlled with a humidistat to prevent overdrying is most common. The first layer may be about 7 ft deep, with successive layers of about 3 ft.

Batch-in-Bin Drying

A storage bin adapted for drying may be used to dry several batches of grain during a harvest season, if the grain is kept to a shallow layer so that higher airflow rates and temperatures can be used. After the batch is dry, the bin is emptied, and the cycle is repeated. The drying capacity of the batch system (bu/yr) is greater than that of other in-storage drying systems. In a typical operation, batches of corn in 3 ft depths are dried from an initial moisture content of 25% with130°F air at the rate of about 20 cfm per cubic foot. Considerable nonuniformity of moisture content may be present in the batch after drying is stopped; therefore, the grain should be well mixed as it is placed into storage. If the mixing is done well, grain that is too wet equalizes in moisture with grain that is too dry before spoilage can occur. Aeration of the grain in storage will facilitate the equalization of moisture.
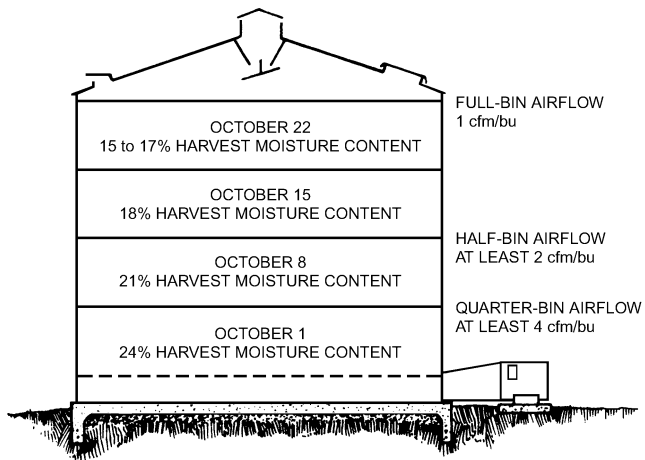
Fig. 7   Example of Layer Filling of Corn

Grain may be cooled in the dryer to ambient temperature before it is stored. Cooling is accomplished by operating the fan without the heater for about 1 h. Some additional drying occurs during the cooling process, particularly in the wetter portions of the batch.

Grain stirring devices are used with both full-bin and batch-in-bin drying systems. Typically, these devices consist of one or more open, 2 in. diameter, standard pitch augers suspended from the bin roof and extending to near the bin floor. The augers rotate and simultaneously travel horizontally around the bin, mixing the drying grain to reduce moisture gradients and prevent overdrying of the bottom grain. The augers also loosen the grain, allowing a higher airflow rate for a given fan. Stirring equipment reduces bin capacity by about 10%. Furthermore, commercial stirring devices are available only for round storage enclosures.

Recirculating/Continuous-Flow Bin Drying

This type of drying incorporates a tapered sweep auger that removes uniform layers of grain from the bottom of the bin as it dries

**Table 7   Recommended Unheated Air Airflow Rate
for Different Grains and Moisture Contents
in the Southern United States**

Type of Grain	Grain Moisture Content, %	Recommended Airflow Rate, cfm per ft³ of grain	cfm/bu
Wheat	25	4.8	6.0
	22	4.0	5.0
	20	2.4	3.0
	18	1.6	2.0
	16	0.8	1.0
Oats	25	2.4	3.0
	20	1.6	2.0
	18	1.2	1.5
	16	0.8	1.0
Shelled Corn	25	4.0	5.0
	20	2.4	3.0
	18	1.6	2.0
	16	0.8	1.0
Ear Corn	25	6.4	8.0
	18	3.2	4.0
Grain Sorghum	25	4.8	6.0
	22	4.0	5.0
	18	2.4	3.0
	15	1.6	2.0
Soybeans	25	4.8	6.0
	22	4.0	5.0
	18	2.4	3.0
	15	1.6	2.0

Compiled from USDA *Leaflet* 332 (1952) and Univ. of Georgia *Bulletin* NS 33 (1958).

RECIRCULATING BATCH DRYER

CONTINUOUS-FLOW DRYER
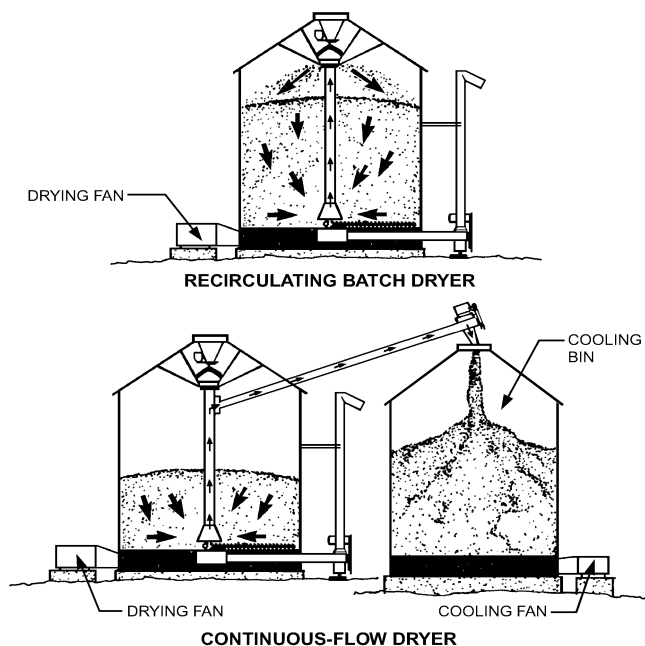
**Fig. 8   Grain Recirculators Convert Bin Dryer to
High-Speed Continuous-Flow Dryer**

(Figure 8). The dry grain is then redistributed on top of the pile of grain or moved to a second bin for cooling. The sweep auger may be controlled by temperature or moisture sensors. When the desired condition is reached, the sensor starts the sweep auger, which removes a layer of grain. After a complete circuit of the bin, the sweep auger stops until the sensor determines that another layer is dry. Some drying takes place in the cooling bin. Up to two percentage points of moisture may be removed, depending on the management of the cooling bin.

DRYING SPECIFIC CROPS

SOYBEANS

Soybeans usually need drying only when there is inclement weather during the harvest season. Mature soybeans left exposed to rain or damp weather develop a dark brown color and a mealy or chalky texture. Seed quality deteriorates rapidly. Oil from weather-damaged beans costs more to refine and is often not of edible grade. In addition to preventing deterioration, the artificial drying of soybeans offers the advantage of early harvest, which reduces the chance of loss from bad weather and reduces natural and combine shatter loss. Soybeans harvested with a wet basis moisture content greater than 13.5% exhibit less damage.

Drying Soybeans for Commercial Use

Conventional corn-drying equipment can be used for soybeans, with some limitations on heat input. Soybeans for commercial use can be dried at 130 to 140°F; drying temperatures of 190°F reduce the oil yield. If the relative humidity of the drying air is below 40%, excessive seedcoat cracking occurs, causing many split beans in subsequent handling. Physical damage can cause fungal growth on the beans, storage problems, and a slight reduction in oil yield and quality. Flow-retarding devices should be used during handling, and beans should not be dropped more than 20 ft onto concrete floors.

Drying Soybeans for Seed and Food

The relative humidity of the drying air should be kept above 40%, regardless of the amount of heat used. The maximum drying temperature to avoid germination loss is 110°F. Natural air drying at a flow rate of 1.6 cfm per cubic foot is adequate for drying seed with an initial moisture content of up to 16% w.b.

If adding heat, raise the drying air temperature no more than 5°F above ambient. This drying method is slow, but it results in excellent quality and avoids overdrying. However, drying must be completed before spoilage occurs. At higher moisture contents, good results have been obtained using an airflow rate of 3.2 cfm per cubic foot with humidity control. Data on allowable drying time for soybeans are unavailable. Without better information, an estimate of storage life for oil crops can be made based on the values for corn, using an adjusted moisture content calculated by the following equation:

$$\text{Comparable moisture content} = \frac{\text{Oilseed moisture content}}{100 - \text{Seed oil content}} \times 100$$

A corn moisture content 2% greater than that of the soybeans should generally be used to estimate allowable drying time (e.g., 12% soybeans are comparable to 14% corn). Soybeans are dried from a lower initial moisture content than corn.

Dry high-moisture soybeans in a bin with the air temperature controlled to keep the relative humidity at 40% or higher. Airflow rates of 8.0 cfm per cubic foot are recommended, with the depth of the beans not to exceed 4 ft.

HAY

Hay normally contains 65 to 80% wet basis moisture at cutting. Field drying to 20% may result in a large loss of leaves. Alfalfa hay leaves average about 50% of the crop by weight, but they contain 70% of the protein and 90% of the carotene. The quality of hay can be increased and the risk of loss due to bad weather reduced if the hay is put under shelter when partially field dried (35% moisture content) and then artificially dried to a safe storage moisture content. In good drying weather, hay conditioned by mechanical means can be dried sufficiently in one day and placed
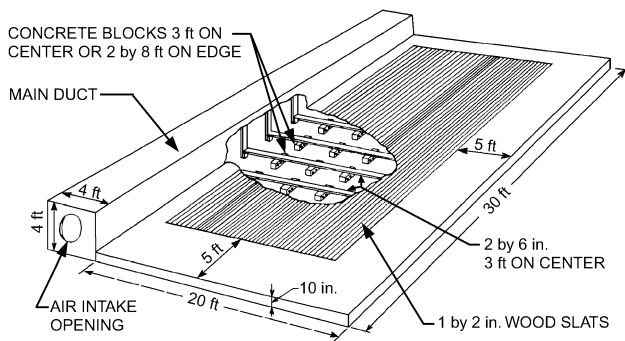
Fig. 9   Central Duct Hay-Drying System with Lateral Slatted Floor for Wide Mows

in the dryer. Hay may be long, chopped, or baled for this operation; unheated or heated air can be used.

In-Storage Drying

Unheated air is normally used for in-storage or mow drying. Hay is dried in the field to 30 to 40% moisture content before being placed in the dryer. For unheated air drying, airflow should be at least 200 cfm per ton. The fan should be able to deliver required airflow against static pressure of 1 to 2 in. of water.

Slotted floors, with at least 50% of the area open, are generally used for drying baled hay. For long or chopped hay in mows narrower than 36 ft wide, the center duct system is the most popular. A slotted floor should be placed on each side of the duct to within 5 ft of its ends and the outside walls (Figure 9). If the mow is wider than 36 ft, it should be divided crosswise into units of 28 ft or narrower. These should then be treated as individual dryers. If the storage depth exceeds about 13 ft, vertical flues and/or additional levels of ducts may be used. If tiered ducts are used, a vertical air chamber, about 75% of the probable hay depth, should be used. The supply ducts are then connected at 7 to 10 ft vertical intervals as the mow is filled. With either of these methods, hay in total depths up to 30 ft can be dried. The duct size should be such that the air velocity is less than 1000 fpm.

The maximum depth of wet hay that should be placed on a hay-drying system at any time depends on hay moisture content, weather conditions, the physical form of the hay, and the airflow rate. The maximum drying depth is about 16 ft for long hay, 13 ft for chopped hay, and 7 small rectangular bales deep for baled hay. Baled hay should have a density of about 8 lb/ft^3. For best results, bales should be stacked tightly together on edge (parallel to the stems) to ensure that no openings exist between them.

For mow drying, the fan should run continuously during the first few days. Afterward, it should be operated only during low relative humidity weather. During prolonged wet periods, the fan should be operated only enough to keep the hay cool.

Batch Wagon Drying

Batch drying can be done on a slotted floor platform; however, because this method is labor-intensive, wagon dryers are more commonly used. With a wagon dryer system, hay is baled at about 45% moisture content to a density of about 11 lb/ft^3. The hay is then stacked onto a wagon with tight, high sides and a slotted or expanded metal floor. Drying is accomplished most efficiently by forcing the heated air (up to 158°F) down the canvas duct of a plenum chamber secured to the top of the wagon. After 4 or 5 h of drying, the exhaust air is no longer saturated with moisture, and about 75% of it may be recirculated or passed through a second wagon of wet hay for greater drying efficiency.

In this method, the amount of hay harvested each day is limited by the capacity of the drying wagons. In this 24 h process, the hay

cut one day is stored the following day; only enough hay to load the drying wagons should be harvested each day.

The airflow rate in this method is normally much higher than when unheated air is used. About 40 cfm per square foot of wagon floor space is required. As with mow drying, the duct size should be such that the air velocity is less than 1000 fpm.

COTTON

Producers normally allow cotton to dry naturally in the field to 12% moisture content or less before harvest. Cotton harvested in this manner can be stored in trailers, baskets, or compacted stacks for extended periods with little loss in fiber or seed quality. Thus, cotton is not normally aerated or artificially dried prior to ginning. Cotton harvested during inclement weather and stored cotton exposed to precipitation must be dried at the cotton gin within a few days to prevent self-heating and deterioration of the fiber and seed.

Though cotton may be safely stored at moisture contents as high as 12%, moisture levels near the upper limit are too high for efficient ginning and for obtaining optimum fiber grade. The cleaning efficiency of cotton is inversely proportional to its moisture content, with the most efficient level being 5% fiber moisture content. However, fiber quality is best preserved when the fiber is separated from the seed at moisture contents between 6.5 and 8%. Therefore, if cotton comes into the system below this level, it can be cleaned, but moisture should be added prior to separating the fiber from the seed to improve the ginning quality. Dryers in the cotton gins are capable of drying the cotton to the desired moisture level.

The tower dryer is the most commonly used among several types of commercially available dryers. This device operates on a parallel flow principle: 14 to 24 cfm of drying air per pound of cotton also serves as the conveying medium. As it moves through the dryer's serpentine passages, cotton impacts on the walls. This action agitates the cotton for improved drying and lengthens its exposure time. Drying time depends on many variables, but total exposure seldom exceeds 15 s. For extremely wet cotton, two stages of drying are needed for adequate moisture control.

Wide variations in initial moisture content dictate different drying amounts for each load of cotton. Rapid changes in drying requirements are accommodated by automatically controlling drying air temperature in response to moisture measurements taken before or after drying. These control systems prevent overdrying and reduce energy requirements. For safety and to preserve fiber quality, drying air temperature should not exceed 350°F in any portion of the drying system.

If the internal cottonseed temperature does not exceed 140°F is unimpaired by drying. This temperature is not exceeded in a tower dryer; however, the moisture content of the seed after drying may be above the 12% level recommended for safe long-term storage. Wet cottonseed is normally processed immediately at a cottonseed oil mill. Cottonseed under the 12% level is frequently stored for several months prior to milling or prior to delinting and treatment at a seed processing plant. The aeration that cools deep beds of stored cottonseed effectively maintains viability and prevents an increase in free fatty acid content. For aeration, ambient air is normally drawn downward through the bed at a rate of at least 0.025 cfm per cubic foot of oil mill seed and 0.125 cfm per cubic foot of planting seed.

PEANUTS

Peanuts normally have a moisture content of about 50% at the time of digging. Allowing the peanuts to dry on the vines in the windrow for a few days removes much of this water. However, peanuts usually contain 20 to 30% moisture when removed from the vines, and some artificial drying is necessary. Drying should begin within 6 h after harvesting to keep the peanuts from self-heating. Both the maximum temperature and the rate of drying must be carefully controlled to maintain quality.

High temperatures result in an off flavor or bitterness. Drying too rapidly without high temperatures results in blandness or nuts that do not develop flavor during roasting. High temperatures, rapid drying, or excessive drying cause the skin to slip easily and the kernels to become brittle. These conditions result in high damage rates in the shelling operation but can be avoided if the moisture removal rate does not exceed 0.5% per hour. Because of these limitations, continuous-flow drying is not usually recommended for peanuts.

Peanuts can be dried in bulk bins using unheated air or air with supplemental heat. Under poor drying conditions, unheated air may cause spoilage, so supplemental heat is preferred. Air should be heated no more than 13 or 14°F to a maximum temperature of 95°F. An airflow rate of 10 to 25 cfm per cubic foot of peanuts should be used, depending on the initial moisture content.

The most common method of drying peanuts is bulk wagon drying. Peanuts are dried in depths of 5 to 6 ft, using airflow rates of 10 to 15 cfm per cubic foot of peanuts and air heated 11 to 14°F above ambient. This method retains quality and usually dries the peanuts in three to four days. Wagon drying reduces handling labor but may require additional investment in equipment.

RICE

Of all grains, rice is probably the most difficult to process without quality loss. Rice containing more than 13.5% moisture cannot be safely stored for long periods, yet the recommended harvest moisture content for best milling and germination ranges from 20 to 26%. When rice is harvested at this moisture content, drying must be started promptly to prevent souring. Normally, heated air is used in continuous-flow dryers, where large volumes of air are forced through 4 to 10 in. layers of rice. Temperatures as high as 130°F may be used, if (1) the temperature drop across the rice does not exceed 20 to 30°F, (2) the moisture reduction does not exceed two percentage points in a 0.5 h exposure, and (3) the rice temperature does not exceed 100°F. During the tempering period following drying, the rice should be aerated to ambient temperature prior to the next pass through the dryer. This removes additional moisture and eliminates one to two dryer passes. It is estimated that full use of aeration following dryer passes could increase the maximum daily drying capacity by about 14%.

Unheated air or air with a small amount of added heat (13°F above ambient, but not exceeding 95°F) should be used for deep-bed rice drying. Too much heat overdries the bottom, resulting in checking (cracking), reduced milling qualities, and possible spoilage in the top. Because unheated air drying requires less investment and attention than supplemental heat drying, it is preferred when conditions permit. In the more humid rice-growing areas, supplemental heat is desirable to ensure that the rice dries. The time required for drying varies with weather conditions, moisture content, and airflow rate. In California, the recommended airflow rate is 0.2 to 2.4 cfm per cubic foot. Because of less favorable drying conditions in Arkansas, Louisiana, and Texas, greater airflow rates are recommended (e.g., a minimum of 2.0 cfm per cubic foot is recommended in Texas). Whether unheated air or supplemental heat is used, the fan should be turned on as soon as rice uniformly covers the air distribution system. The fan should then run continuously until the moisture content in the top 1 ft of rice is reduced to about 15%. At this point, the supplemental heat should be turned off. The rice can then be dried to a safe storage level by operating the fan only when the relative humidity is below 75%.

STORAGE PROBLEMS AND PRACTICES

MOISTURE MIGRATION

Redistribution of moisture generally occurs in stored grain when grain temperature is not controlled (Figure 10). Localized spoilage can occur even when the grain is stored at a safe moisture
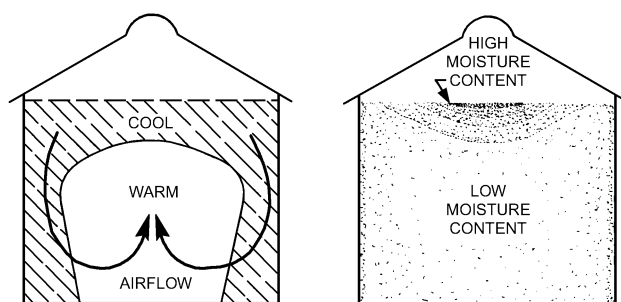
Fig. 10   Grain Storage Conditions Associated with Moisture Migration During Fall and Early Winter

level. Grain placed in storage in the fall at relatively high temperatures cools nonuniformly through contact with the outside surfaces of the storage bin as winter approaches. Thus, the grain near the outside walls and roof may be at cool outdoor temperatures while the grain nearer the center is still nearly the same temperature it was at harvest. These temperature differentials induce air convection currents that flow downward along the outside boundaries of the porous grain mass and upward through the center. When the cool air from the outer regions contacts the warm grain in the interior, the air is heated and its relative humidity is lowered, increasing its capacity to absorb moisture from the grain. When the warm, humid air reaches the cool grain near the top of the bin, it cools again and transfers vapor to the grain. Under extreme conditions, water condenses on the grain. The moisture concentration near the center of the grain surface causes significant spoilage if moisture migration is uncontrolled. During spring and summer, the temperature gradients are reversed. The grain moisture content increases most at depths of 2 to 4 ft below the surface. Daily variations in temperature do not cause significant moisture migration. Aside from seasonal temperature variations, the size of the grain mass is the most important factor in fall and winter moisture migration. In storages containing less than 1200 ft^3, there is less trouble with moisture migration. The problem becomes critical in large storages and is aggravated by incomplete cooling of artificially dried grain. Artificially dried grain should be cooled to near ambient temperature soon after drying.

GRAIN AERATION

Aeration by mechanically moving ambient air through the grain mass is the best way to control moisture migration. Aeration systems are also used to cool grain after harvest, particularly in warmer climates where grain may be placed in storage at temperatures exceeding 100°F. After the harvest heat is removed, aeration may be continued in cooler weather to bring the grain to a temperature within 20°F of the coldest average monthly temperature. The temperature must be maintained below 50°F.

Aeration systems are not a means of drying because airflow rates are too low. However, in areas where the climate is favorable, carefully controlled aeration may be used to remove small amounts of moisture. Commercial storages may have pockets of higher-moisture grain if, for example, some batches of grain are delivered after a rain shower or early in the morning. Aeration can control heating damage in the higher-moisture pockets.

Aeration Systems Design

Aeration systems include fans capable of delivering the required amount of air at the required static pressure, suitable ducts or floors to distribute the air into the grain, and controls to regulate the operation of the fan. The airflow rate determines how many hours are required to cool the crop (Table 8). Most aeration systems are designed with airflow rates between 0.05 and 0.2 cfm/bu.

Stored grain is aerated by forcing air up or down through the grain. Upward airflow is more common because it is easier to observe when the cooling front has moved through the entire grain mass. In large, flat storages with long ducts, upward airflow results in more uniform air distribution than downdraft systems.

During aeration, a warming or cooling front moves through the crop (Figure 11); it is important to run the fan long enough to move the front completely through the crop.

Static pressure for an aeration system can be determined using the airflow resistance information in Chapter 11 of the 2005 *ASHRAE Handbook—Fundamentals.* All common types of fans are used in aeration systems. Attention should be given to noise levels with fans that are operated near residential areas or where people work for extended periods. The supply ducts connecting the fan to the distribution ducts in the grain should be designed and constructed according to the standards of good practice for any air-moving application. A maximum air velocity of 2500 fpm may be used, but 1600 to 2000 fpm is preferred. In large systems, one large fan may be attached to a manifold duct leading to several distribution ducts in one or more storages, or smaller individual fans may serve individual distribution ducts. Where a manifold is used, valves or dampers should be installed at each takeoff to allow adjustment or closure of airflow when part of the aerator is not needed.

Distribution ducts are usually perforated sheet metal with a circular or inverted U-shaped cross section, although many functional arrangements are possible. The area of the perforations should be at least 10% of the total duct surface. The holes should be uniformly spaced and small enough to prevent the passage of the grain into the duct (e.g., 0.1 in. holes or 0.08 in. wide slots do not pass wheat).

Since most problems develop in the center of the storage, and the crop cools naturally near the wall, the aeration system must provide good airflow in the center. Flush floor systems work well in storages with sweep augers and unloading equipment. Ducts should be easily removable for cleaning. Duct spacing should not exceed the depth of the crop; the distance between the duct and storage structure wall should not exceed one-half the depth of the crop for bins and flat storages. Common duct patterns for round bins are shown in Figure 12. Duct spacing for flat storages is shown in Figure 13.

When designing the distribution duct system for any type of storage, the following should be considered: (1) the cross-sectional area and length of the duct, which influences both the air velocity within the duct and the uniformity of air distribution; (2) the duct surface area, which affects the static pressure losses in the grain surrounding the duct; and (3) the distance between ducts, which influences the uniformity of airflow.

For upright storages where distribution ducts are relatively short, duct velocities up to 2000 fpm are permissible. Maximum recommended air velocities in ducts for flat storages are shown in Table 9. Furthermore, these velocities should not be exceeded in the air outlets from the storage; therefore, an air outlet area at least equal to the duct cross-sectional area should be provided.

The duct surface area that is perforated or otherwise open for air distribution must be great enough that the air velocity through the grain surrounding the duct is low enough to avoid excessive pressure loss. When a semicircular perforated duct is used, the entire surface area is effective; only 80% of the area of a circular duct resting on the floor is effective. For upright storages, the air velocity through the grain near the duct (duct face velocity) should be limited to 30 fpm or less; in flat storages, to 20 fpm or less.

Duct strength and anchoring are important. If ducts placed directly on the floor are to be held in place by the crop, the crop flow should be directly on top of the ducts to prevent movement and damage. Distribution ducts buried in the grain must be strong enough to withstand the pressure the grain exerts on them. In tall, upright storages, static grain pressures may reach 10 psi. When ducts are located

Table 8 Airflow Rates Corresponding to Approximate Grain Cooling Time

Airflow Rate, cfm/bu	Cooling Time, h
0.05	240
0.1	120
0.2	60
0.3	40
0.4	30
0.5	24
0.6	20
0.8	15
1.0	12

Table 9 Maximum Recommended Air Velocities Within Ducts for Flat Storages

Grain	Airflow Rate, cfm/bu	Air Velocity (fpm) within Ducts for Grain Depths of:				
		10 ft	20 ft	30 ft	40 ft	50 ft
Corn, soybeans, and other large grains	0.05	—	750	1000	1250	1250
	0.1	750	1000	1250	1500	1750
	0.2	1000	1250	—	—	—
Wheat, grain sorghum, and other small grains	0.05	—	1000	1500	1750	2000
	0.1	750	1500	2000	—	—
	0.2	1000	2000	—	—	—

NEGATIVE-PRESSURE AERATION

POSITIVE-PRESSURE AERATION
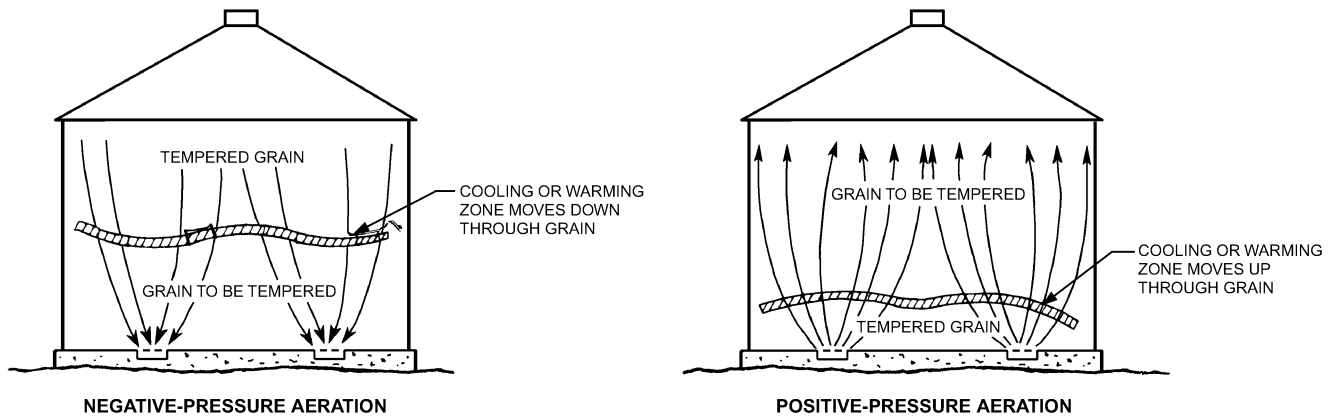
Fig. 11   Aerating to Change Grain Temperature

in the path of the grain flow, as in a hopper, they may be subjected to many times this pressure during grain unloading.

Operating Aeration Systems

The operation of aeration systems depends largely on the objectives to be attained and the locality. In general, cooling should be carried out any time the outdoor air temperature is about 15°F cooler than the grain. Stored grain should not be aerated when the air humidity is much above the equilibrium humidity of the grain because moisture will be added. The fan should be operated long enough to cool the crop completely, but it should then be shut off and covered, thus limiting the amount of grain that is rewetted.

Aeration to cool the grain should be started as soon as the storage is filled, and cooling air temperatures are available. Aeration to prevent moisture migration should be started whenever the average air temperature is 10 to 15°F below the highest grain temperature.
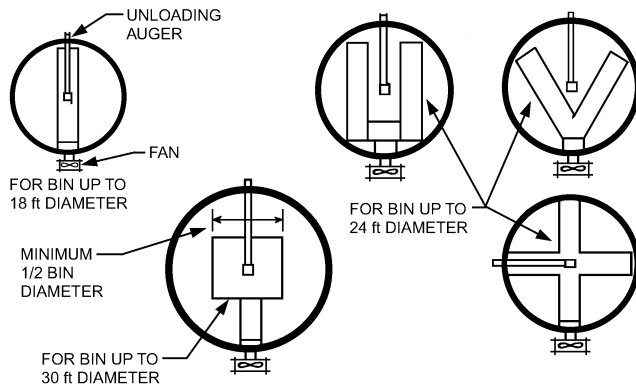
Aeration is usually continued as weather permits until the grain is uniformly cooled to within 20°F of the average temperature of the coldest month, or to 30 to 40°F.

Grain temperatures of about 32 to 50°F are desirable. In the northern corn belt, aeration may be resumed in the spring to equalize the grain temperature and raise it to between 40 and 50°F. This reduces the risk of localized heating from moisture migration. Storage problems are the only reason to aerate when air temperatures are above 60°F. Aeration fans and ducts should be covered when not in use.

In storages where fans are operated daily in fall and winter months, automatic controls work well when air is not too warm or humid. One thermostat usually prevents fan operation when the air temperature is too high, and another prevents operation when the air is too cold. A humidistat allows operation when the air is not too humid. Fan controllers that determine the equilibrium moisture content of the crop based on existing air conditions can regulate the fan based on entered information.

SEED STORAGE

Seed must be stored in a cool, dry environment to maintain viability. Most seed storages have refrigeration equipment to maintain a storage environment of 45 to 55°F. Seed storage conditions must be achieved before mold and insect damage occur.

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Fig. 12   Common Duct Patterns for Round Grain Bins
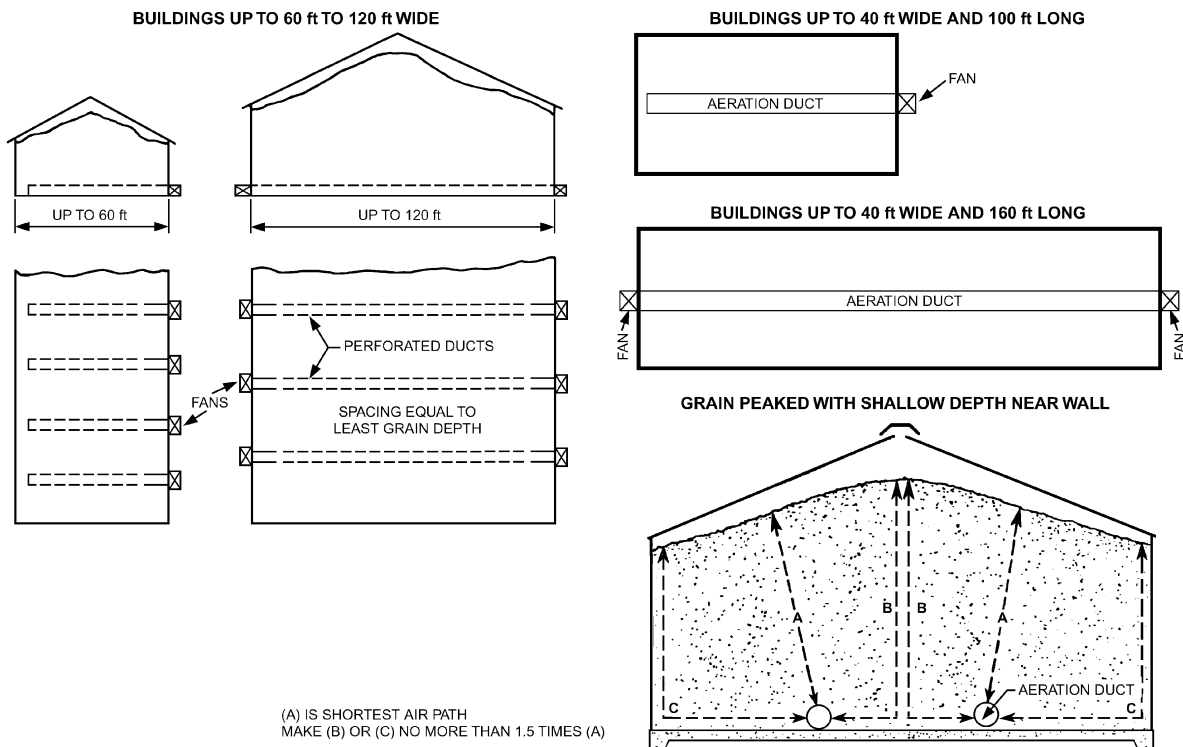
Fig. 13   Duct Arrangements for Large Flat Storages

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CHAPTER 24

AIR CONDITIONING OF WOOD AND PAPER PRODUCT FACILITIES

THIS chapter covers some of the standard requirements for air conditioning of facilities that manufacture finished wood products as well as pulp and paper.

GENERAL WOOD PRODUCT OPERATIONS

In wood product manufacturing facilities, ventilation can be considered a part of the process. Metal ductwork should be used and grounded to prevent a buildup of static electricity. Hoods should be made of spark-free, noncombustible material. A pneumatic conveying system should be furnished to reduce the accumulation of wood dust in the collecting duct system. The airflow rate and velocity should be able to maintain the air-dust mixture below the minimum explosive concentration level. If dampers are unavoidable in the system, they should be firmly fastened after balancing work. Dust collectors should be located outside of the building. Fans or blowers should be placed downstream of the dust collector and air-cleaning equipment, and should be interlocked with the wood-processing equipment. When the fan or blower stops, the wood process should stop immediately and forward a signal to the alarm system.

Deflagration venting and suppression should be furnished for wood-processing workshops and wood-processing equipment such as vessels, reactors, mixers, blenders, mills, dryers, ovens, filters, dust collectors, storage equipment, material-handling equipment,

The preparation of this chapter is assigned to TC 9.2, Industrial Air Conditioning.

and aerosol areas. The deflagration suppression system must be disarmed before performing any maintenance work to avoid possible injury from discharging the suppressant. Warning signs should be displayed prominently at all maintenance access points.

Finished lumber products to be used in heated buildings should be stored in areas that are heated 10 to 20°F above ambient. This provides sufficient protection for furniture stock, interior trim, cabinet material, and stock for products such as ax handles and glue-laminated beams. Air should be circulated within the storage areas. Lumber that is kiln-dried to a moisture content of 12% or less can be kept within a given moisture content range through storage in a heated shed. The moisture content can be regulated either manually or automatically by altering the dry-bulb temperature (Figure 1).

Some special materials require close control of moisture content. For example, musical instrument stock must be dried to a given moisture level and maintained there because the moisture content of the wood affects the harmonics of most stringed wooden instruments. This control may require air conditioning with reheat and/or heating with humidification.

Process Area Air Conditioning

Temperature and humidity requirements in wood product process areas vary according to product, manufacturer, and governing code. For example, in match manufacturing, the match head must be cured (i.e., dried) after dipping. This requires careful control of humidity and temperature to avoid a temperature near the ignition point. Any process involving application of flammable substances

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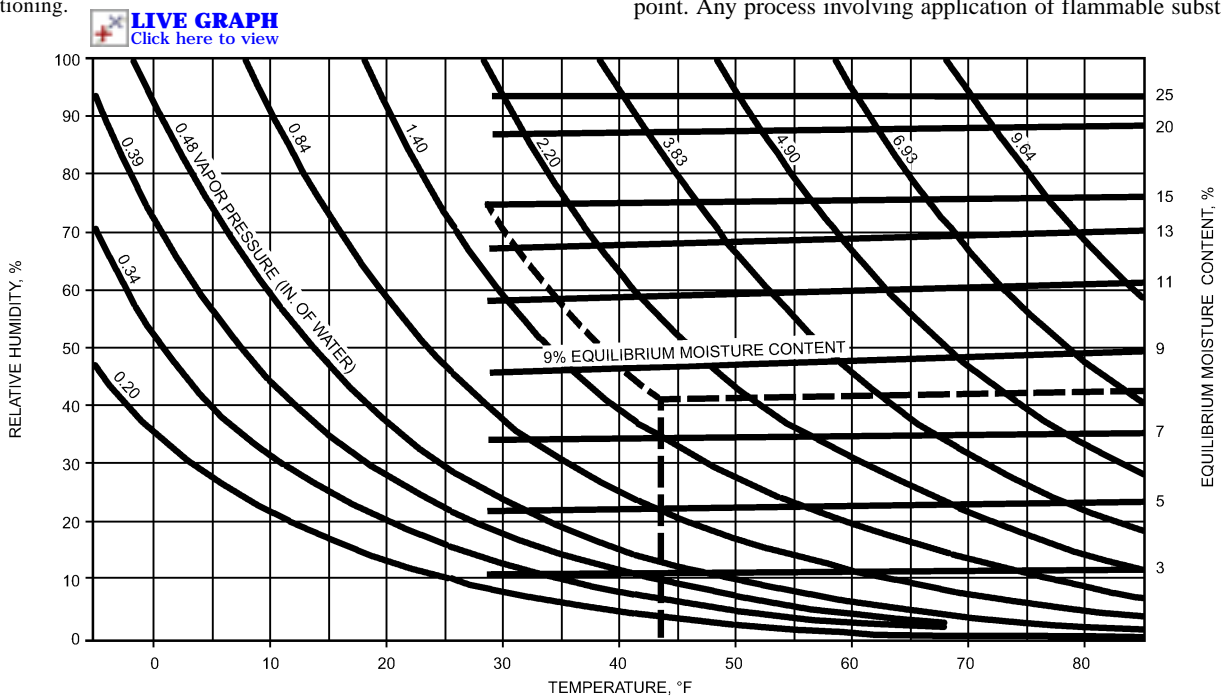
Fig. 1   Relationship of Temperature, Relative Humidity, and Vapor Pressure of Air and Equilibrium Moisture Content of Wood

should follow the ventilation recommendations of the National Fire Protection Association, the National Fire Code, and the U.S. Occupational Safety and Health Act.

Finished Product Storage

Finished lumber to be made into furniture, equipment parts, musical instruments, architectural woodwork, or other wood products of value is stored and/or manufactured under controlled temperature and humidity to maintain proper wood dryness. Improper drying can cause laminated or glued joints to fail. Finished wood that has changed dimension because of excess moisture gain or loss can cause fitting problems. Cracking, splitting, checking, warping, and discoloring are other problems with improperly dried and/or stored wood.

Green, rough, cut lumber is stacked end to end in layers, each layer being separated by wood strips to allow air circulation. Lumber can be stacked and left to dry naturally in open-sided sheds. Enclosed, heated kilns with steam coils and/or direct steam injection, forced air circulation, makeup air, and exhaust air vents could be used where faster, controlled drying is preferred. Drying (or addition of moisture) can be accomplished by HVAC systems using dehumidifying coils and/or desiccants, heating/reheat coils, humidifiers, makeup and exhaust air, distribution air ducts, and automatic controls. An insulated dehumidifying/humidifying room could be constructed and finished to minimize moisture migration from higher-humidity areas. Lumber can also be dried by solar kilns, microwaves, dielectric heating, superheated steam, and vacuum.

Wood is composed of natural fibers and its moisture content varies according to its environment. Samples from the wood being dried must be tested for moisture content at predetermined time intervals to prevent overdrying and defects. Drying rates are determined by the wood species. Final moisture content depends upon the wood's ultimate use.

The formula for determining moisture content is

$$\frac{\left[\binom{\text{Weight of sample}}{\text{when cut}} - \binom{\text{Weight of oven-}}{\text{dried sample}}\right] \times 100}{\text{Weight of oven-dried sample}} = \frac{\text{Moisture}}{\text{content, \%}}$$

Lumber/wood drying using HVAC systems can be accomplished with factory- or field-assembled systems. The quantity of lumber/wood to be dried, wood species, rate of drying, total moisture removal, drying room construction, economics (cost and rate of return on investment), fire and safety codes, maintenance, and ease of use influence the type of HVAC system to be installed.

PULP AND PAPER OPERATIONS

The papermaking process comprises two basic steps: (1) wood is reduced to pulp (i.e., wood fibers), and (2) the pulp is converted to paper. Wood can be pulped by either mechanical action (e.g., grinding in a groundwood mill), chemical action (e.g., kraft pulping), or a combination of both.

Many different types of paper can be produced from pulp, ranging from the finest glossy finish to newsprint to bleached board to fluff pulp for disposable diapers. To make newsprint, a mixture of mechanical and chemical pulps is fed into the paper machine. To make kraft paper (e.g., grocery bags, corrugated containers), however, only unbleached chemical pulp is used. Disposable diaper material and photographic paper require bleached chemical pulp with a very low moisture content of 6 to 9%.

Paper Machine Area

In papermaking, extensive air systems are required to support and enhance the process (e.g., by preventing condensation) and to provide reasonable comfort for operating personnel. Radiant heat from steam and hot-water sources and mechanical energy dissipated

as heat can result in summer temperatures in the machine room as high as 120°F. In addition, high paper machine operating speeds of 2000 to 4500 fpm and a stock temperature near 122°F produce warm vapor in the machine room.

Outside air makeup units and process exhausts absorb and remove room heat and water vapor released from the paper as it is dried (Figure 2). Makeup air is distributed to working areas above and below the operating floor. Part of the air delivered to the basement migrates to the operating floor through hatches and stairwells. Motor-cooling equipment distributes cooler basement air to the paper machine drive motors.

Wet and basement exhaust should be installed inside the room. Outside air intakes with insulated adjustable louvers should be installed on the outside wall to supplement the mechanical air supply. In facilities with no basement exterior wall, sufficient mechanical air intake should be provided. The exhaust, adjustable louver, or mechanical air intake should be furnished with modulating control. When the ambient temperature drops to near freezing, outside airflow must be reduced to a minimum and the appropriate heater started to prevent freezing.

The most severe ventilation demand occurs in the area between the wet-end forming section and press section and the dryer section. In the forming section, the pulp slurry, which contains about 90% water, is deposited on a traveling screen. Gravity, rolls, foils, vacuum, steam boxes, and three or more press roll nips are sequentially used to remove up to 50% of the water in the forming section and press section. The wet end is very humid because of evaporation of moisture and mechanical generation of vapor by turning rolls and cleaning showers. Baffles and a custom-designed exhaust in the forming section help control the vapor. A drive-side exhaust in the wet end removes heat from the motor vent air and removes the process generated vapor.

To prevent condensation or accumulated fiber from falling on the traveling web, a false ceiling is used with ducts connected to roof exhausters that remove humid air not captured at a lower point. At the wet end, heated inside air is usually circulated to scrub the underside of the roof to prevent condensation in cold weather. Additional roof exhaust may also remove accumulated heat from the dryer section and the dry end during warmer periods. Ventilation in the wet end should be predominantly by roof exhaust.

The large volume of moisture and vapor generated from the wet-end process rises and accumulates under the roof. To keep condensation from forming in winter, the roof is normally exhausted and hot air is distributed under the roof. Sufficient roof insulation should be installed to keep the inside surface temperature above the dewpoint. Heat transfer from the room to the interior surface is
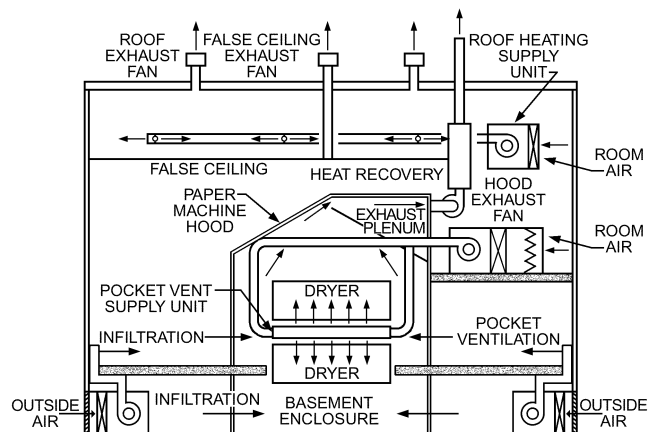
Fig. 2   Paper Machine Area

$$\frac{t_r - t_{is}}{R_{r-is}} = \frac{t_{is} - t_o}{R_{is-o}} \qquad (1)$$

where

t_r = room air temperature, °F
t_{is} = roof interior surface temperature, °F
t_o = outside air temperature, °F
R_{r-is} = heat transfer resistance from room air to roof interior surface. In winter, $R_{r-is} = 0.61$ ft^2·°F·h/Btu
R_{is-o} = required total R-value from roof interior surface to outside air, ft^2·°F·h/Btu

For a given project, t_o and t_r have been determined and only t_{is} needs to be selected. For wet-end roof insulation and assuming 96% relative humidity, t_{is} can be shown on a psychrometric chart to be

$$t_{is} = t_r - 1.2°F \qquad (2)$$

Then Equation (1) can be simplified to find the required roof R-value as

$$R_{is-o} = \frac{0.61}{1.2}(t_r - t_o - 1.2) \qquad (3)$$

In the dryer section, the paper web is dried as it travels in a serpentine path around rotating steam-heated drums. Exhaust hoods remove heat from the dryers and moisture evaporated from the paper web. Most modern machines have enclosed hoods, which reduce the airflow required to less than 50% of that required for an open-hood exhaust. The temperature inside an enclosed hood ranges from 130 to 140°F at the operating floor to 180 to 200°F in the hood exhaust plenum at 70 to 90% rh, with an exhaust rate generally ranging from 300,000 to 400,000 cfm.

Where possible, pocket ventilation air (see Figure 3) and hood supply air are drawn from the upper level of the machine room to take advantage of the preheating of makeup air by process heat as it rises. The basement of the dryer section is also enclosed to control infiltration of machine room air to the enclosed hood. The hood supply and pocket ventilation air typically operate at 200°F; however, some systems run as high as 250°F. Enclosed hood exhaust is typically 300 cfm per ton of machine capacity. The pocket ventilation and hood supply are designed for 75 to 80% of the exhaust, with the balance infiltrated from the basement and machine room. Large volumes of air (500,000 to 800,000 cfm) are required to balance the paper machine's exhaust with the building air balance.

The potential for heat recovery from hood exhaust air should be evaluated. Most of the energy in steam supplied to the paper dryers is converted to latent heat in the hood exhaust as water evaporates from the paper web. Air-to-air heat exchangers are used where the air supply is located close to the exhaust. Air-to-liquid heat exchangers that recirculate water/glycol to heat remote makeup air units can also be used. Air-to-liquid systems provide more latent
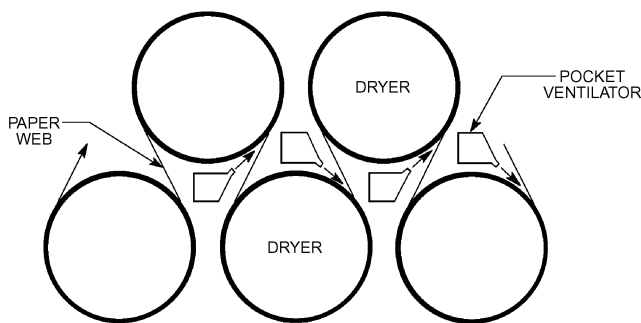
heat recovery, resulting in three to four times more total heat recovery than air-to-air units. Some machines use heat recovered from the exhaust air to heat process water. Ventilation in paper machine buildings in the United States ranges from 10 to 25 air changes per hour in northern mills to 20 to 50 in southern mills. In some plants, computers monitor the production rate and outside air temperature to optimize operation and conserve energy.

After fine, bond, and cut papers have been bundled and/or packaged, they should be wrapped in a nonpermeable material. Most papers are produced with less than 10% moisture by weight, the average being 7%. Dry paper and pulp are hygroscopic and begin to swell noticeably and deform permanently when the relative humidity exceeds 38%. Therefore, finished products should be stored under controlled conditions to maintain their uniform moisture content.

Finishing Area

To produce a precisely cut paper that stabilizes at a desirable equilibrium moisture content, the finishing areas require temperature and humidity control. Further converting operations such as printing and die cutting require optimum sheet moisture content for efficient processing. Finishing room conditions range from 70 to 75°F db and from 40 to 45% rh. Rooms should be maintained within reasonably close limits of the selected conditions. Without precise environmental control, the paper equilibrium moisture content varies, influencing dimensional stability, the tendency to curl, and further processing.

Process and Motor Control Rooms

In most pulp and paper applications, process control, motor control, and switchgear rooms are separate from the process environment. Air conditioning removes heat generated by equipment, lights, etc., and reduces the air-cleaning requirement. (See Chapter 17 for air conditioning in control rooms that include a computer, a computer terminal, or data processing equipment.) Ceiling grilles or diffusers should be located above access aisles to avoid the risk of condensation on control consoles or electrical equipment during start-up and recovery after an air-conditioning shutdown. Electrical rooms are usually maintained in the range of 75 to 80°F, with control rooms at 73°F; the humidity is maintained in the range of 45 to 55% in process control rooms and is not normally controlled in electrical equipment rooms.

Motor and electrical control rooms for process and electrical distribution control contain electronic equipment that is susceptible to corrosion. The typical pulp and paper mill environment contains both particulate and vapor-phase contaminants with sulfur- and chloride-based compounds. To protect equipment, multistage particulate and adsorbent filters should be used. They should have treated activated charcoal and potassium permanganate-impregnated alumina sections for vapor-phase contaminants, as well as fiberglass and cloth media for particulates.

Switchgear and motor control centers are not as heat-sensitive as control rooms, but the moisture-laden air carries chemical residues onto the contact surfaces. Arcing, corrosion, and general deterioration can result. A minimum amount of filtered, outside air and air conditioning is used to protect these areas.

In most projects, the electric distribution control system (DCS) is energized before the room air conditioning is installed and started. If a temporary air conditioner is used in the DCS room, a condensate drain pan and temporary drain pipe should be installed to keep condensate from the cable channel beneath the DCS panels.

Paper Testing Laboratories

Design conditions in paper mill laboratories must be followed rigidly. The most recognized standard for testing environments for paper and paper products (paperboard, fiberboard, and containers) is TAPPI (the Technical Association of the Pulp and Paper Industry) *Standard* T402. Other standards include ASTM E171 and ISO/TC 125.

Fig. 3   Pocket Ventilation

Standard pulp and paper testing laboratories have three environments: preconditioning, conditioning, and testing. The physical properties of a sample are different if it is brought to the testing humidity from a high humidity than if it is brought from a lower humidity. Preconditioning at lower relative humidity tends to eliminate hysteresis. For a preconditioning atmosphere, TAPPI *Standard* T402 recommends 10 to 35% rh and 72 to 104°F db. Samples are usually conditioned in a controlled, conditioned cabinet.

Conditioning and testing atmospheres should be maintained at $50 \pm 2.0\%$ rh and $73 \pm 2°F$ db. However, a change of 2°F db at 73°F without starting a humidifier causes the relative humidity to fluctuate as much as 3%. A dry-bulb temperature tolerance of $\pm 1°F$ must be held to maintain a $\pm 2\%$ rh. A well-designed temperature and humidity control system should be provided.

Miscellaneous Areas

The pulp digester area contains many components that release heat and contribute to dusty conditions. For batch digesters, the chip feeders are a source of dust and need hooded exhaust and makeup air. The wash and screen areas have numerous components with hooded exhausts that require considerable makeup air. Good ventilation controls fumes and humidity. The lime kiln feed-end releases extremely large amounts of heat and requires high ventilation rates or air conditioning.

Recovery-boiler and power-boiler buildings have conditions similar to those of power plants; the ventilation rates are also similar. The control rooms are generally air conditioned. The grinding motor room, in which groundwood is made, contains many large motors that require ventilation to keep the humidity low.

System Selection

The system and equipment selected for air conditioning a pulp and paper mill depends on many factors, including the plant layout and atmosphere, geographic location, roof and ceiling heights (which can exceed 100 ft), and degree of control desired. Chilled-water systems are economical and practical for most pulp and paper operations, because they have both the large cooling capacity needed by mills and the precision of control to maintain the proper temperature and humidity in laboratories and finishing areas. In the bleach plant, the manufacture of chlorine dioxide is enhanced by using water with a temperature of 45°F or lower; this water is often supplied by the chilled-water system. If clean plant or process water is available, water-cooled chillers are satisfactory and may be supplemented by water-cooled direct-expansion package units for small, remote areas. However, if plant water is not clean enough, a separate cooling tower and condenser water system should be installed for the air conditioning.

Most manufacturers prefer water-cooled over air-cooled systems because of the gases and particulates present in most paper mills. The most prevalent contaminants are chlorine gas, caustic soda, borax, phosphates, and sulfur compounds. With efficient air cleaning, the air quality in and about most mills is adequate for properly placed air-cooled chillers or condensing units that have properly applied coil and housing coatings. Phosphor-free brazed coil joints are recommended in areas where sulfur compounds are present.

Heat is readily available from processing operations and should be recovered whenever possible. Most plants have good-quality hot water and steam, which can be used for unit heater, central station, or reheat quite easily. Evaporative cooling should be considered. Newer plant air-conditioning methods, using energy conservation techniques such as temperature destratification and stratified air conditioning, have application in large structures. Absorption systems should be considered for pulp and paper mills because they provide some degree of energy recovery from the high-temperature steam processes.

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CHAPTER 25

POWER PLANTS

THIS chapter discusses HVAC systems for industrial facilities for the production of process heat and power and for electrical generating stations. Not every type of power plant is specifically covered, but the process areas addressed normally correspond to similar process areas in any plant. For example, wood-fired boilers are not specifically discussed, but the requirements for coal-fired boilers generally apply.

Aspects of HVAC system design unique to nuclear power plants are covered in Chapter 26.

GENERAL DESIGN CRITERIA

Space-conditioning systems in power plant buildings are designed to maintain an environment for reliable operation of power generation systems and equipment and for the convenience and safety of plant personnel. A balance is achieved between the cost of the process systems designed to operate in an environment and the cost of providing that environment.

Environmental criteria for personnel safety and comfort are governed by several sources. The U.S. Occupational Safety and Health Administration (OSHA) defines noise, thermal environment, and air contaminant exposure limits. Chapters 12 and 29 of this volume and *Industrial Ventilation* by the American Conference of Governmental Industrial Hygienists (ACGIH 2004) also provide guidance for safety in work spaces, primarily in the areas of industrial ventilation and worker-related heat stress. The degree of worker comfort is somewhat subjective and more difficult to quantify. The plant owner or operator ordinarily establishes the balance between cost and worker comfort.

Exhaust vents are subject to regulation of the plant's air quality permit and local air pollution control board's requirements. For this reason, all exhaust vent locations should be properly identified and classified, and coordinated with the plant's environmental compliance department. Treatment of exhaust streams is discussed in Chapter 25 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*.

Criteria should be clearly defined at the start of design, because they document an understanding between the process designer and the HVAC system engineer that is fundamental to achieving the environment required for the various process areas. Typical criteria for a coal-fired power plant are outlined in Table 1. They should be reviewed for compliance with local codes, the plant operator's experience and preferences, and the overall financial objectives of the facility. Additional discussion of criteria may be found in the sections on specific areas.

The preparation of this chapter is assigned to TC 9.2, Industrial Air Conditioning.

Temperature and Humidity

Selection of outdoor design temperatures is based on the operating expectations of the plant. If the power production facility is critical and must operate during severe conditions, then the effect of local extreme high and low temperatures on the systems should be evaluated. Electrical power consumption is usually highest under extreme outdoor conditions, so the plant should be designed to operate when needed the most. Other temperature ranges, indicated in Table 1, may be more appropriate for less-critical applications.

Indoor temperatures should match the specified operating temperatures of the equipment. Electrical equipment, such as switchgear, motor control centers, and motors, typically determines the design temperature limits in the plant; common temperature ratings are 104 or 122°F. Other areas such as elevator machine rooms may include electronic equipment with temperature restrictions.

In plant areas where compressed-gas containers are stored, the design temperature is according to the gas supplier. Typically, the minimum temperature should be high enough that the gas volume can be effectively released from the containers. If the gas is hazardous (e.g., chlorine), the minimum temperature does not apply during personnel occupancy periods, when high dilution ventilation rates are needed.

Practical ventilation rates for fuel-fired power plants provide indoor conditions 10 to 20°F above the outdoor ambient. Therefore, ventilation design criteria establish a temperature rise above the design outdoor temperature to produce an expected indoor temperature that matches the electrical equipment ratings. For example, an outdoor extreme design temperature of 112°F with a ventilation system designed for a 10°F rise would meet the requirements of 122°F-rated plant equipment unless a new record temperature occurred. However, the environment for workers should also be considered. Velocity (spot) cooling may be necessary in some areas to support work activities.

Low temperatures may affect plant reliability because of the potential for freezing. The selection of the low design temperature should be balanced by the selection of the heating design margin. If the record low temperature is used in the design, indoor design temperatures of 35 to 40°F may be used. In the heating system design, credit is generally not taken for heat generated from operating equipment.

The selection of outdoor design humidity levels affects the selection of cooling towers and evaporative cooling processes and the sizing of air-conditioning coils for outdoor air loads. When values from Chapter 28 of the 2005 *ASHRAE Handbook—Fundamentals* are used for design, the mean coincident wet bulb is appropriate. If extreme dry-bulb temperatures are selected for the design basis, the use of extreme wet bulbs is too restrictive because the extremes are not coincident. It is prudent to use the wet bulb associated with the 1% dry bulb when extreme dry-bulb temperatures are used for the design.

Table 1 Design Criteria for Fuel-Fired Power Plant

Building/Area	Design Outdoor Cooling/Heating Dry-Bulb[a]	Indoor Temperature, °F Maximum	Minimum	Relative Humidity, %	Room Ventilation Rate, ach*	Filtration Efficiency, %	Pressur-ization	Redundancy[b]	Noise Criterion
Steam Turbine Area									
Suboperating level	0.4%/99.6%	Design outdoor + 10	45	None	30	None	None	Multiplicity	Background
Above operating floor	0.4%/99.6%	Design outdoor + 10	45	None	10	None	None	Multiplicity	Background
Combustion Turbine Area	0.4%/99.6%	Design outdoor + 18	45	None	20	None	None	Multiplicity	Background
Steam Generator Area									
Below burner elevation	0.4%/99.6%	Design outdoor + 10	45	None	30	None	None	Multiplicity	Background
Above operating floor	0.4%/99.6%	Design outdoor + 10	45	None	15	None	None	Multiplicity	Background
Air-Conditioned Areas[d]									
Control rooms and control equipment rooms containing instruments and electronics	Extreme (see text)	75 ± 2	72 ± 2	30 to 65	ASHRAE *Std.* 62.1	85 to 90 (see text)	Positive	100%	NC-40[c]
Offices	1%/99%	78	70	30 to 65	ASHRAE *Std.* 62.1	ASHRAE *Std.* 62.1	Positive	None	See text
Laboratories	1%/99%	78	70	30 to 65	ASHRAE *Std.* 62.1	High	Positive	None	See text
Locker rooms and toilets	1%/99%	78	70	None	ASHRAE *Std.* 62.1	ASHRAE *Std.* 62.1	Negative	None	See text
Shops (not air-conditioned)	1%/99%	Design outdoor + 10	65	None	15	None	None	None	85 dBA
Mechanical Equipment									
Pumps, large power	0.4%/99.6%	Design outdoor + 10	45	None	30	None	None	Multiplicity	Background
Valve stations, miscellaneous	0.4%/99.6%	Design outdoor + 10	45	None	15	None	None	None	85 dBA
Elevator machine rooms	0.4%/99.6%	90	45	None	None	Low	Positive	None	85 dBA
Fire pump area	0.4%/99.6%	NFPA *Std.* 20	NFPA *Std.* 20	None	NFPA *Std.* 20	None	None	None	85 dBA
Diesel generator area	0.4%/99.6%	Design outdoor + 10	45	None	30	None	None	None	Background
Electrical Equipment[d]									
Enclosed transformer equipment areas	0.4%/99.6%	Design outdoor + 10	45	None	60	Low	Positive	100%	85 dBA
Critical equipment	Extreme (see text)	Design outdoor + 10	45	None	30	None	None	100%	85 dBA
Miscellaneous electrical equipment	0.4%/99.6%	Design outdoor + 10	45	None	20	None	None	Multiplicity	85 dBA
Water Treatment									
Chlorine equipment rooms									
When temporarily occupied	0.4%/99.6%	Design outdoor + 10	None	None	60	None	Negative	None	85 dBA
When unoccupied	0.4%/99.6%	Design outdoor + 10	60	None	15	None	Negative	None	85 dBA
Chemical treatment	0.4%/99.6%	Design outdoor + 10	60	None	10	None	None	None	85 dBA
Battery Rooms	0.4%/99.6%	77	77	None	As required for hydrogen dilution	None	Negative or neutral	50%	85 dBA

*Listed numbers are for estimating purposes only. When heat gain data are available, use Equation (1) to calculate required ventilation rate.
[a]See Chapter 28 of the 2005 *ASHRAE Handbook—Fundamentals* for design dry-bulb temperature data corresponding to given annual cumulative frequency of occurrence and specific geographic location of plant.

[b]Multiplicity indicates that the HVAC system should have multiple units.
[c]See Figure 6 in Chapter 7 of the 2005 *ASHRAE Handbook—Fundamentals* for noise criterion curves.
[d]See ASHRAE Research Project RP-1104 (White 2003) for heat release values.

Indoor design humidity is not a factor in ventilated areas unless the plant is in a harsh, corrosive environment. In this case, lower humidity reduces the potential for corrosion. In air-conditioned areas for personnel or electronic equipment, ASHRAE *Standard* 62.1, Instrumentation, Systems, and Automation Society (ISA) *Standard* S71-04, and manufacturers' recommendations dictate the humidity criteria.

Ventilation Rates

Ventilation within plant structures provides heat removal and dilution of potentially hazardous gases. Ventilation rates for heat removal are calculated during HVAC system design to meet summer indoor design temperatures.

The numbers shown in Table 1 for air change rates are for estimating approximate ventilation needs. Actual heat emission rates should be obtained from equipment manufacturers or from the engineer's experience. American Boiler Manufacturer's Association (ABMA) heat loss curves (Stultz and Kitto 1992) can be used to approximate heat loads from boiler casings if better information is not available.

The ventilation rate for room heat removal is

$$Q = \frac{q}{(t_r - t_o)(60 \rho c_p)} \qquad (1)$$

where

> Q = ventilation rate, cfm
> q = room heat, Btu/h
> t_r = allowed room temperature from Table 1, °F
> t_o = outside air temperature, °F
> ρ = air density, lb_m/ft^3
> c_p = specific heat of air = 0.24 $Btu/lb_m \cdot$°F

Hazardous gases are mostly handled by the process system design functions. Natural gas and other combustible fuel gases are controlled by ignition safeties and may contain odorants for detection. Hydrogen and other gases used for generator and bus cooling are monitored for leakage by pressure loss or makeup rates. Escaped gases are diluted by outside air infiltration. For a building with very tight construction (i.e., very little natural infiltration), an analysis should be performed to verify that dilution rates are acceptable.

Flue gas is confined to the boiler and flue gas ductwork and generally poses no hazard. In some types of boilers and associated gas ducts, however, flue gas is at a higher pressure than the surroundings and can leak into occupied areas. Also, special treatment gases such as ammonia or sulfur compounds encountered in flue gas conditioning systems can leak into the boiler building, depending on the location of the treatment device in the flue gas stream. In these cases, gas detection monitors should be used.

Ventilation for areas with hazardous gases (e.g., chlorine) should be designed by specific gas industry standards such as *The Chlorine Manual* (CI 1997) or ACGIH (2004).

Infiltration and Exfiltration

Infiltration of outside air into boiler and power-generation structures or exfiltration of room air from these buildings is driven by thermal buoyancy of heated air. Both infiltration and exfiltration are beneficial; infiltration air dilutes fugitive fumes, whereas exfiltration air carries out excess heat during hot weather. However, infiltration adds to the cold-weather load on the heating system.

Filtration and Space Cleanliness

Filtration of ventilation air for process areas is usually not needed because some process areas are dirtier than the outdoor surroundings, and the process equipment is designed to operate in a dusty environment. However, the plant may be located in an area with sources of outdoor particulate contaminants that need to be managed to protect the process equipment. Power plants in dusty or sandy areas, or where there are seasonal nuisances such as airborne plant matter, may require filtration of ventilation air. Plants at industrial sites such as refineries and paper mills may need to address gaseous contaminants and corrosive gases, as well.

Indoor air cleanliness is a concern in control room HVAC system design. Even if the control center is in an independent building, remote from the boiler-turbine building, other operations such as coal transportation, coal crushing, fuel/air distribution and combustion, ash handling, fume heat recovery, fume/smoke exhaust diffusion, and so forth may contaminate the entire plant and its surroundings.

When potential outdoor contaminants are a factor, the quality of outdoor air may need to be evaluated. This may include collection of typical particulates and the use of corrosion coupons to quantify gaseous contaminants. The U.S. Environmental Protection Agency (EPA) is a source of data. Filtration requirements may include 30% dust-spot test efficiency prefilters, 65 to 90% efficiency final filters, and gas-phase filtration units.

Air-conditioned areas for people should meet ASHRAE *Standard* 62.1 requirements. Air-conditioned areas for control and electrical equipment should meet the requirements of the equipment manufacturer(s). Guidelines for reliability of electrical equipment are found in ISA *Standard* S71.04.

Redundancy

Maintaining design operating temperatures within the power plant is essential for reliable operation. Operating electrical equipment above its rated temperature reduces equipment life. Sensitive electronic equipment, such as in the main control center, may not function reliably at high temperatures. Low temperatures also affect plant availability; for example, low temperatures in batteries or freezing of pipes, instrument lines, or tanks could prevent normal plant operation.

The HVAC systems or components essential for plant operation should be designed with redundancy to ensure plant availability. Automatic switchover to the back-up system may be required in normally unoccupied areas. In areas where back-up systems are impractical, temperature monitoring and alarming systems should be considered to initiate temporary corrective measures.

HVAC systems that include multiple units (indicated as "multiplicity" in Table 1) also improve power plant reliability. A space ventilated by multiple fans, such as four at 1/4 capacity, may retain sufficient ventilation even if one fan is out of service.

Noise

Consideration should be given to noise levels produced by HVAC system equipment both inside and outside plant spaces. Indoor noise guidelines should be established for air-conditioned areas and ventilated areas with continuous occupancies. Outdoor noise levels are established by the environmental noise pollution concerns of adjacent areas.

Air-conditioned indoor spaces should meet the normal sound level guidelines for occupancies (such as offices) listed in Chapter 47. Special occupancies such as control rooms should follow the guidelines in Table 1.

Ventilated areas of the plant should be treated as other industrial areas following OSHA regulations. Sound levels indicated in Table 1 are suggested guidelines that may be appropriate in the absence of a specific engineered solution to meet the OSHA requirements. Where "background" is indicated in Table 1, noise generated by HVAC equipment is usually not a major noise source in comparison to the noise from processes or equipment such as turbine generators, motors, pumps, and relieving of process steam. In these areas, overall noise level criteria are established by the process equipment requirements.

HVAC system components contribute to the overall noise level outside the plant buildings either by generating noise or by having ventilation openings. HVAC designs for power plants in urban areas can be significantly influenced by outdoor noise level requirements. Equipment may have to include sound-absorbing materials or be located indoors in sound attenuation enclosures. Openings may require acoustical louvers.

VENTILATION APPROACH

Summer ventilation can be achieved by natural draft, forced mechanical supply and exhaust, or natural and mechanical combined systems. **Natural-draft systems** use a combination of adjustable inlet louvers and open doors or windows and relieve warmed air through roof or high side-wall openings. **Mechanical systems** use fans, power roof ventilators (PRVs), or air-handling units to move air. A **combined system** typically uses lower and upper wall and roof openings for natural ventilation while using mechanical ventilation as a supplement. With any ventilation arrangement, consideration should be given to physical separation of inlet and outlet openings to minimize recirculation, as discussed in Chapter 16 of the 2005 *ASHRAE Handbook—Fundamentals*.

APPLICATIONS

Large plants or units with layouts containing large ducts and equipment in the ventilation airflow path, possibly with limited separation between pieces of major equipment and/or exterior walls, imposing a pressure drop exceeding the capability of gravity ventilation systems, require mechanical assistance. The plant design may have cavities, such as the area under the boiler arch and between the casing and flue gas duct (see Figures 1 and 2), which require mechanical ventilation. Areas of the plant such as the conveyor gallery usually require mechanical assistance in the makeup air system to ensure pressurization control and proper functioning of dust collectors and associated equipment.

Natural or gravity systems are appropriate for facilities without basements and with relatively open airflow paths. The pressure drop of intake louvers, control dampers, powerhouse airflow path, and exhaust louvers/gravity vents should not exceed the minimum expected buoyancy forces. Care should also be taken to configure the system so as not to interfere with mechanical dust collection equipment.

In any system configuration, the engineer should ensure all areas of the plant are provided airflow. Air intakes and supply ducts/fans should be located to prevent short-circuiting with relief openings. Ventilation air should be supplied to electrical boards and other equipment located in upper elevations of the plant, because these areas are usually significantly hotter than the lower elevations.

Driving Forces

Natural ventilation systems use the thermal buoyancy of the air as the motive force for air movement through a building. Equations for determining differential pressures for natural ventilation are found in Chapter 27 of the 2005 *ASHRAE Handbook—Fundamentals*. With natural ventilation, air enters the enclosed space and is heated by the plant equipment. The difference in density between the inside air and the outside air causes air to be drawn into the building at low elevations and relieved at high elevations.

Mechanical ventilation depends on fans (or fans and buoyancy forces) to provide required ventilation regardless of the building configuration or the temperature difference.

Air Distribution

With natural ventilation, small differential pressures drive air movement. Accordingly, air is drawn into the building at low velocities; it penetrates a short distance into the building and then disperses.

Mechanical ventilation supplied from the walls or roof can distribute air more effectively throughout the structure.

A combined system uses both natural and mechanical ventilation to achieve effective air distribution and prevent air stagnation A typical combined system uses lower-level sidewall openings as the primary natural air intake and roof or upper-level sidewall openings for hot air relief. The location and size of openings can prevent hot air accumulation under the roof naturally. Mechanical ventilation should be provided where sufficient airflow cannot be established.

Inlet and Exhaust Areas

Because of the low differential pressure driving the air, natural ventilation requires numerous large inlet louver and exhaust relief areas. Mechanical ventilation requires fewer openings.

Noise

Openings required for natural ventilation allow noise generated by inside plant equipment to pass more easily to the outside.

Mechanical equipment such as fans and PRVs generate noise directly, but the noise level can be managed by fan selection and acoustical treatment.

Impact on Plant Cleanliness

Natural ventilation creates negative pressure in the lower portions of the building, which may draw dust and fumes into the building through openings near ground level.

Mechanical ventilation can pressurize the building and can draw air from relatively clean sources at higher elevations.

Economics

The primary advantage to natural ventilation is that there are no operating costs for fan power. Because natural ventilation is passive, it is more reliable and has lower maintenance costs than a mechanical system. However, natural ventilation may not always be the most economical selection. The cost of louvers and inlet openings, architectural features, and gravity relief openings to achieve an acceptable ventilation rate may be higher than the first cost for mechanical ventilation.

Another consideration is the average building temperature. Because internal heat is the driving force, the naturally ventilated building is normally warmer than the power-ventilated building. This warmer average temperature may shorten the life of plant equipment such as expansion joints, seals, motors, electrical switchgear, and instrumentation. Warmer temperatures may also affect operator performance.

The large louver areas associated with natural ventilation may allow greater infiltration, thereby increasing the winter heating load. This additional heating cost may offset some of the summer energy savings of natural ventilation.

A combined system takes on the strengths of both natural and mechanical ventilation and can offer the advantages of reduced capital and operating costs.

STEAM GENERATOR BUILDINGS: INDUSTRIAL AND POWER FACILITIES

A steam generator is a device that uses heat energy to convert water to steam. The two basic subsystems of a steam generator are the heat energy system and the steam process system.

The heat energy system for a fueled (oil, gas, coal, etc.) steam generator includes fuel distribution piping or conveyors, preparation subsystems, and supply rate and ignition controls. Provision to supply and regulate combustion air is required at the combustion chamber; flue gas is handled downstream of the combustion area. With ash-producing fuels, bottom ash below the steam generator and fly ash entrained in the flue gas must be processed. Figure 1 shows a steam generator building with typical components.

Steam process components typically found in the steam generator building include an enclosure for the fire and heat transfer surfaces and feedwater equipment such as pumps, piping, and controls. Steam lines for primary and reheat steam are typically routed from the steam drum and reheat sections of the steam generator to the steam turbine or process systems.

The heat energy and steam process systems impose requirements on the HVAC systems for specific areas of the steam generator building.

Burner Areas

Fuel (gas, oil, coal, etc.) is transferred to the furnace, mixed with combustion air, and ignited in the burner area of the steam generator. Instrumentation must modulate the fuel in response to combustion needs. Viewports typically allow operators to monitor combustion. In many cases, these viewports are equipped with aspirating air systems to limit the amount of flue gas and heat escaping the boiler and entering the boiler room.

The burner area requires special attention for the steam generator building ventilation system. This area is often occupied by plant operators who monitor and inspect the controls and the combustion process. Heat is radiated and conducted to the adjacent spaces from
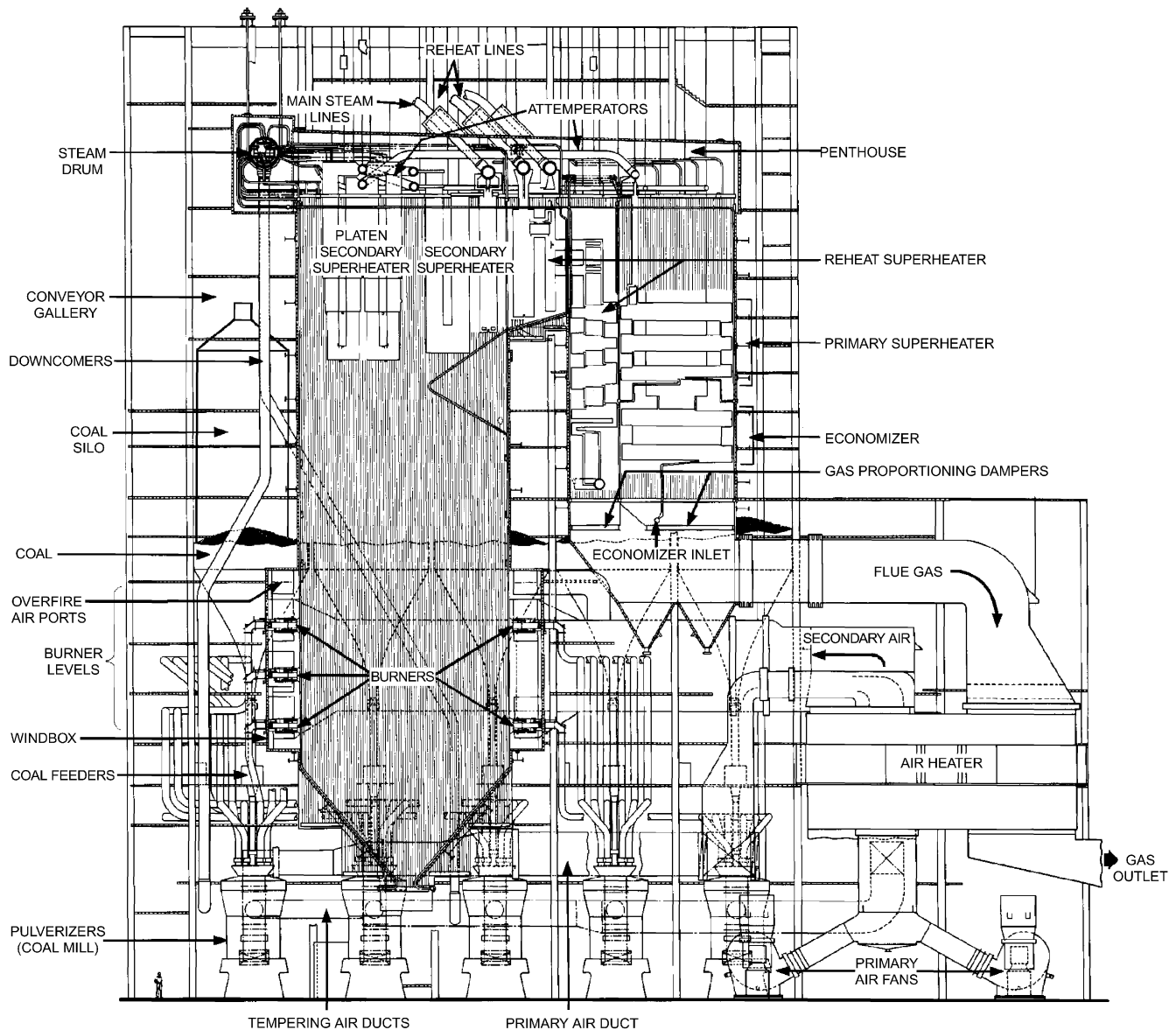
Fig. 1   Steam Generator Building
(Courtesy The Babcock & Wilcox Company)

inspection ports, penetrations, and the steam generator. Leakage of fumes and combustion gases is also possible.

Both the burner area operator and the controls require ventilation with outdoor air. Outdoor air also provides dilution for fugitive fumes. Outdoor air can be ducted to burner areas and discharged by supply registers or blown directly into the area with wall-mounted fans, depending on the building arrangement. The flow rate is difficult to quantify; generally, 60 air changes per hour supplied to an area 15 to 20 ft around the steam generator provide adequate ventilation. Consider providing velocity cooling of personnel workstations. In cold climates, outdoor air may need to be tempered with indoor air.

Steam Drum Instrumentation Area

A typical steam generator has a steam drum at the top of the boiler that provides the water-to-steam interface. The water level in the drum is monitored to regulate the flow of steam and feedwater. This is a critical steam generator control function, so accurate and reliable process flow measurement is important.

The steam drum instrumentation area may include sections of uninsulated furnace surface, which conducts and radiates heat to the surrounding area. The ventilation system should remove this heat to ensure that area temperatures are within instrumentation temperature limits. Instrumentation may need to be shielded from hot surfaces. Velocity cooling may be needed at operator workstations.

Wall-mounted panel fans in the outside walls are an option for providing ventilation air during warm weather. Heating is generally not a concern unless the steam generator is expected to be out of service during cold weather.

Local Control and Instrumentation Areas

In addition to the drum and burners, the steam generator building may house local control areas for functions such as fuel supply, draft fans, or ash handling. Because areas around a steam generator may be hot and dirty, the location and selection of the control equipment should be coordinated between the electrical system engineer and the HVAC system engineer.

The alternatives are to (1) locate the control equipment remotely from the steam generator, (2) use electrical components that can withstand the environment, or (3) provide a local environmentally controlled enclosure. The first alternative requires additional cable and raceway and perhaps additional signal boosters and conditioners. The second alternative requires more robust electrical equipment that can tolerate extremely hot or dirty areas.

When the electrical and control system design dictates that the equipment be located near the steam generator, a dedicated enclosure with a supporting environmental control system may be necessary. A typical environmental control system may control an air-handling unit capable of providing adequate filtration, pressurization, and temperature control. The temperature control may be obtained with a chilled-water or direct-expansion (DX) coil with a remote condensing unit. An air-cooled condensing unit may be used if it is rated to match the surroundings.

Coal- and Ash-Handling Areas

Coal is typically stored on site, either in piles or in storage structures. Material-handling equipment moves the coal to conveyors for transportation to preconditioning equipment (e.g., a crusher). Processed coal is conveyed to steam generator building storage silos. Coal feed equipment regulates the supply of coal from the silos either to the burner or to final processing equipment such as pulverizing mills.

Many new power plants are designed to burn low-cost coals from Wyoming's Powder River Basin and other similar coal seams. Many of these coals are extremely friable when dry, creating significant amounts of dust during handling. During new plant design, the material handling and ventilation systems should be designed to control dusting, preferably by using modern chutework and coal-handling machinery design to reduce or control dust emissions during fuel handling. This can reduce the effects of mechanical dust collectors and associated makeup air on plant HVAC systems.

Some coals spontaneously begin to burn during normal outdoor ambient weather and normal powerhouse interior conditions. Under some conditions, accumulated coal dust spontaneously smolders, then suddenly flashes if the surface crust of the pile is broken, exposing the smoldering coal to oxygen. It is important that equipment in areas subject to dust accumulation be designed to reduce dust accumulation with sloped or curved surfaces, and designed to facilitate manual cleaning and washdown. Spontaneous combustion must be addressed in ventilation and dust collector design and installation to facilitate emptying dust out of the collector without exposing plant personnel to fire and explosion hazards.

Coal-handling areas in the steam generator building that require special ventilation system consideration are the conveyor, silo, feeder, mill, and their transition areas, and ash-handling areas.

Conveyor Areas. Primary concerns are dust control, outgassing from the coal, freezing of the coal and personnel access areas, and fire protection. Dust can be a concern because of the potential for environmental emission and also as a personnel and/or explosive hazard. Dust may be controlled by water-based spray systems or by air induction pickups at the point of generation. Some types of coal may outgas small quantities of methane, which could accumulate in the conveyor and storage structures. See the section on Coal Crusher and Coal Transportation System Buildings for a discussion of ventilation of methane fumes.

Natural or forced ventilation must remove heat from conveyor motors, other equipment, and envelope loads. Ventilation air can also remove outgassed fumes. Generally, ventilation requirements can be as low as 2 to 5 air changes per hour. If air entrainment dust collection equipment is used, provisions for makeup should be included in the design. If natural openings are not sufficient for makeup air, supply ventilation fans may need to be electrically interlocked to operate with the dust suppression/collection equipment. Makeup air may have to be heated if freeze protection is a design

criterion. Unit heaters are generally used for spot heating. The unit heater should be specified to the hazard classification for the area it serves. Because coal dust can produce acids when wet, consideration should be given to specifying noncorrosive materials and coatings.

NFPA *Standard* 120 and the U.S. Bureau of Mines (1978) provide other safety considerations for coal handling and preparation areas.

Silo and Feeder Areas. Coal is generally fully contained by feeders and silos, so no special ventilation is needed. Occasionally, coal systems include an inert gas purge system for fire prevention. Ventilation may be needed for life safety dilution ventilation of purge gases.

Coal Mill Areas. Coal mills require large power motors for the grinding process. These motors may have their own ventilation system, or the motor heat may be rejected directly to the surrounding space.

The challenge for the ventilation system is to provide enough ventilation to remove heat without creating high air velocities that disturb accumulated dust. Blowing dust can pose health risks to operators and create a dust ignition hazard. Although occurrence of dust ignition air-to-dust ratios is possible, this area is generally not classified as hazardous. The dust ignition risk is managed by housekeeping, maintenance of seals on the mill equipment, and other dust-control measures.

Forced supply ventilation is generally required for equipment cooling. Sidewall propeller fans work well if the mills are arranged near outside walls. Mills located in the interior of the building may require ducted supply air. Supply air velocities at the coal-handling equipment must be lower than the particulate entrainment velocity for the expected dust size. The maximum air velocity is established using the particle size distribution spectrum and the associated air settling velocities indicated in Figure 3 and Table 1 in Chapter 12 of the 2005 *ASHRAE Handbook—Fundamentals*.

Many utilities use carbon monoxide (CO) monitoring/trending to detect fires in coal bunkers, silos, and other areas. These systems are sometimes integrated with dust collector and other exhaust streams in these areas. Specification and design of the CO monitoring should be the responsibility of a special hazards fire protection engineer and coordinated with the industrial ventilation and HVAC design.

The National Fire Protection Association (NFPA) does not differentiate between coal types/seams in the codes and standards. The utility industry, however, has accumulated experience and established best practices in handling these fuels. This information is shared between member utilities through groups such as Edison Electric Institute and Electric Power Research Institute. Other sources of specific requirements include local fire code authorities and the plant's insurance carrier.

Ash-Handling Areas. Ash is generated when coal or heavy fuel oil is burned. Fine ash particles carried by the flue gas from the top of the steam generator are called **fly ash**. Ash that accumulates as slag in the bottom of the steam generator is called **bottom ash**.

Ash-handling equipment generally demands no special HVAC system consideration. Although fly ash is captured in the flue gas stream by a baghouse or electrostatic precipitator, uncaptured (fugitive) fly ash can create problems in equipment mechanisms because of its abrasiveness. If fugitive fly ash is expected to be in the air, HVAC equipment in the ash-handling areas should include filters to capture the ash before it enters building areas.

Stack Effect

One consideration in HVAC system design for a steam generator building is the stack effect caused by buoyancy of heated air. A 300 ft tall steam generator building with 0°F outdoor air temperature and 100°F indoor air temperature may have 0.5 in. of water negative internal pressure at ground level. This high level of negative pressure
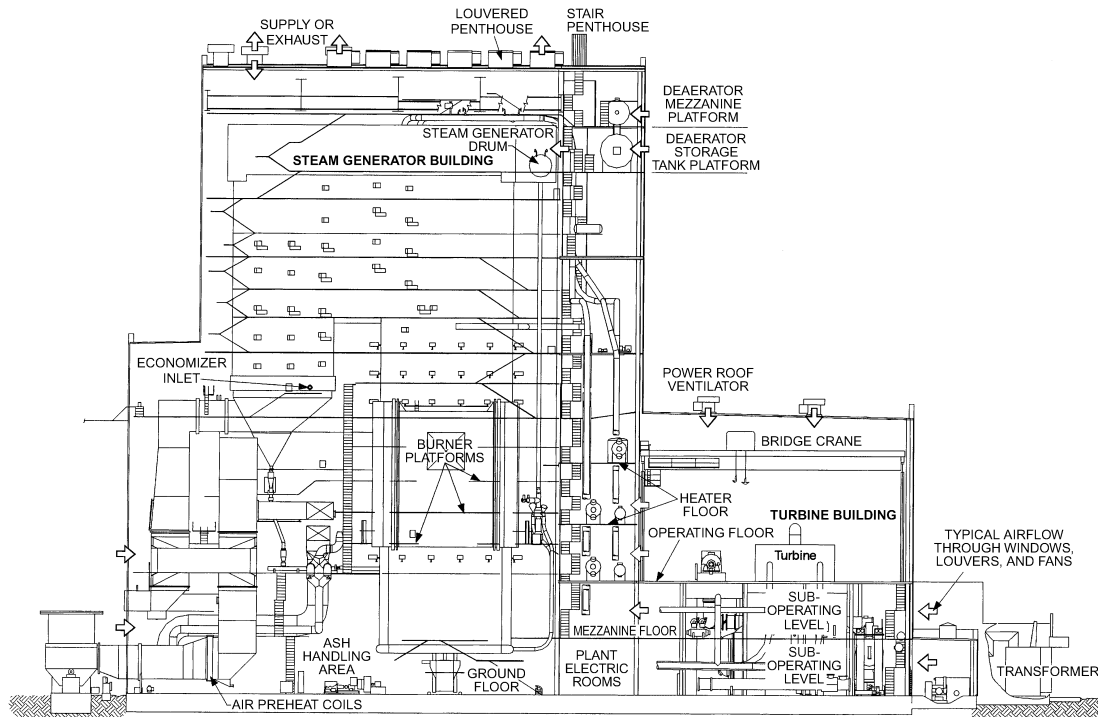
Fig. 2   Generation Building Arrangement
(Courtesy Black & Veatch LLP)

causes abnormally large forces on doors, creating a hazard for operators.

Sources of Combustion Air

Large-draft fans supply combustion air for the steam generator. A positive-pressure steam generator is supplied by forced-draft fans, and a negative-pressure steam generator uses induced-draft fans. A balanced-draft steam generator, typical for a larger unit, uses both forced- and induced-draft fans. Because the air is heated to furnace temperatures in the combustion process, part of the fuel energy is used to heat the air. Forced-draft fans on a large steam generator can supply 100,000 cfm or more to the combustion process. A significant amount of energy is needed to preheat the combustion air.

Two prevailing methods of preheating combustion air are used. One method is to draw air in from outdoors and heat it using steam or hot-water coils using energy directly from the power cycle. Another method uses heat rejected from steam generator surfaces to the building space to heat combustion air. This method provides energy savings over heating outdoor air. Temperatures in the higher levels of the generator building can be 100°F or higher. Heat recovery is accomplished by locating the draft fan intake high in the building. Although the potential for savings is large in a cold climate, the total effect on the building heating and ventilation systems should be evaluated. One effect is that drawing the air from the building makes the building pressure more negative; this increases infiltration and adds to the building heating system load, possibly offsetting the potential power cycle thermal efficiency advantage. Increased negative pressure can also contribute to stack effect problems associated with negative pressure low in the building. The draft fan can also be used to supplement ventilation during warm outdoor conditions.

TURBINE GENERATOR BUILDING

As shown in Figure 2, a turbine generator building usually includes a high-bay operating level, a deaerator mezzanine, and one or more suboperating levels. Typically, the turbines and elec-

tric generators are located along the centerline of the building between the operating level and the first suboperating level and are the major heat sources in the building. Deaerators are another significant heat contributor; the deaerator mezzanine is commonly open to the turbine operating level. Other room heat sources are steam, steam condensate and hot-water piping, heat exchangers, steam valve stations and traps, motors, electric transformers, and other electrical equipment.

Local Control and Instrumentation Areas

Some power plants include a local turbine-generator control panel on the operating floor. The local control panel area of the turbine generator may be either enclosed or open; for the enclosed arrangement, the environmental requirements are the same as those given in the Main Control Center section.

For an open arrangement, velocity cooling with conditioned air improves the operator's working environment. Because the area may be directly exposed to high-temperature surroundings, the recommended velocity of the conditioned air discharge is 300 to 600 fpm, depending on its service distance and workers' preference. The air distribution system should have manually adjustable air deflectors for operator comfort. In addition, the control panel may need a separate cooling source.

Deaerator Mezzanine

The deaerator and associated storage tank reject significant heat at the deaerator mezzanine level. This plant area also typically includes instrumentation and control equipment enclosures; accordingly, the area should have local ventilation to provide the necessary cooling.

Bridge Crane Operating Rooms

Outside air entering the building is heated by process heat, rises toward higher elevation, and is relieved through openings. The bridge crane operating room is as high as the roof beam and within the building exhaust airstream. If the outside air temperature is 95°F,

the crane operating room may be surrounded by 105°F or hotter air. Hence, the bridge crane operating room is normally air conditioned.

Because the bridge crane operating room moves within the building during its operation, through-the-wall mounted air conditioners are commonly used; to simplify the electrical work, an additional power plug in the crane for the air conditioner should be provided by the crane supplier. Provisions for the cooling-coil condensate drain should be included in the design.

Suboperating Level

The turbine generator is located on the operating floor, a large deck surface open to the turbine building roof. The deck may be 70% or more of the turbine building area. Below the operating level are one or more suboperating levels. Ventilation supply air should be provided to the suboperating levels and at the lower elevations of the operating floor. Air rising through the operating levels brings room heat to the roof area, where it is relieved through high-elevation openings (gravity vents) or exhausted by roof-mounted exhaust fans or PRVs.

The major heat sources in the suboperating levels are high-temperature mechanical and piping systems. Other contributors are electric transformer room exhaust, switchgear room exhaust, electric reactor room exhaust, electric motor heat, etc. Electrical equipment exhaust heat in the turbine generator building is small compared to heat emitted from mechanical and piping systems. Accordingly, ventilation air from the plant distribution electric room can generally be exhausted directly into the turbine building without ducting to the outside. Conditioned air may be supplied to local instrumentation panel areas.

For plants in cold climates (temperatures below 32°F), consider spot heating and/or exterior door heated-air curtains. Consideration should also be given to freeze protection of piping close to building walls; stack effect and wind-driven infiltration can increase local heating requirements at the building perimeter. This problem can be addressed by adding capacity to installed heating systems or by providing mobile, temporary heating.

Electric Transformer Rooms

Transformer rooms are typically located at a suboperating level between the turbine building and steam generator buildings. For isolation of dust, the transformer rooms should not have inlet openings to the steam generator building.

The transformer room exhaust air temperature should not exceed the design limit of the transformers. Typically, air intake is from a turbine building suboperating level or from outdoors, and exhaust air discharges at the higher level of the transformer room toward the turbine building.

Plant Electrical Distribution Equipment and Switchgear/MCC Rooms

Air for the main station switchgear and motor control center (MCC) rooms should be relatively clean. Supply air from outdoors should be filtered with 30% efficiency air filters. Air can be relieved through louvers into the plant or to the outside.

A similar approach is used for the ventilation system for an electric reactor room. If the reactors have ducted connections for the exhausts, a removable section may be required so that the ducts can be disassembled when the reactor is lifted during maintenance.

Isophase Bus Duct Cooling

Power from the generator is conveyed by isophase bus ducts to the main transformer. This generates heat, which must be dissipated to a heat sink. A specialized forced-air system is used to cool the isophase bus duct. The duct cooler consists of cooling coils, fans, dampers, and filters. For a low-velocity system, air is supplied to the cooler along two phases of the bus duct and returned in the third phase. For a higher-velocity system, air is supplied and returned

midway between the transformer and generator, or is supplied at the generator end along bus ducts of all three phases and returned at the transformer end. Isophase bus cooling is essential for power production and delivery, so it is important that the designer specify sufficient redundancy (in the form of dual fans, dual cooling coils and a bypass duct to provide cooling with outside air, or another source) in the system design.

COMBUSTION TURBINE AREAS

Combustion turbines are adaptable for outdoor or indoor installation. The outdoor type is usually a skid-mounted structure, with support systems typically designed and furnished by the combustion turbine vendor. The indoor type is typically enclosed in a weatherproof and acoustically treated enclosure and may have indoor support systems, designed and installed separately.

Combustion turbine installations have some or all of the following support facilities: fuel oil handling facility, natural gas pressure-reducing facility, office or administration areas, maintenance shops, battery rooms, control rooms, distributed control system (DCS) control room, communication or computer room, and a water treatment facility. Heating and ventilation design issues associated with combustion turbines include but are not limited to airflow, combustion air source, hot duct and equipment surfaces, fuel supply, turbine inlet cooling, and noise.

The turbine manufacturer typically establishes HVAC requirements and, if required by the purchaser, provides HVAC equipment for the various compartments on the turbine skid. Turbine ventilation and equipment requirements should be coordinated with the building ventilation design.

Turbine and generator casings and the surface of the exhaust duct are large contributors to the heat removal requirements. Hot surfaces should be insulated with appropriate materials as much as is practical and with the approval of the turbine manufacturer, with appropriate airflow established to eliminate hot spots.

When heat recovery equipment is installed in the turbine exhaust, the designer must take into consideration the additional heat rejected into the building because of increased back pressure on the hot exhaust.

Airflow through the combustion turbine building should consider combustion air requirements, combustible gas dilution requirements based on design leakage rates, heat removal requirements, exhaust gas dilution, and electrical component cooling requirements. Combustion turbines draw combustion air through ducts from outside the building. The system design should ensure control of the building pressurization to keep the building under positive pressure, and building outdoor air should be filtered. This also offsets infiltration of dust, rain, snow, bugs, and other contaminants into the building. System design should address freeze protection for vulnerable components. For cold-climate applications during normal operation, mixing outdoor and building air to keep the outdoor supply air temperature above freezing is recommended. In electrically classified installations, the ventilation system must switch to 100% outdoor air during upset conditions.

Noise from combustion turbines is managed by a combination of site location considerations, acoustic enclosures; sound attenuation devices and engineered sound controls included those that are part of on HVAC Systems.

HVAC design requirements for various areas of the building or turbine skid may be obtained from Table 1. The design should use NFPA *Standards* such as 37, 70, and 90A; insurance carrier requirements; and applicable local codes and standards. HVAC system design and operation should be coordinated with the fire protection systems to ensure adequate concentration of fire suppressant and to prevent fire and smoke spread. HVAC systems also must shut down when fire or extremely high concentrations of gases are detected.

MAIN CONTROL CENTER

The main control center usually comprises a control room, a battery room, a communication equipment room, electronic and electric control panel rooms, and associated administration areas.

Because the control center usually contains temperature-sensitive electronic equipment critical to plant operation, it is generally provided with redundant air-handling units and refrigeration equipment. A back-up power supply may also be required. Passive components such as distribution ductwork and piping do not have to be duplicated. Controls should be designed so that failure of a component common to both the primary and back-up systems does not cause failure of both systems. Manual changeover is a simple solution to this problem.

Control Rooms

The control room houses the computerized microprocessor, printer, electronic and emergency response controls, fire protection controls, communication and security systems, regional system networks, accessories, and relevant wiring and tubing systems. An air-conditioning system typical for office occupancy, with features to meet overall design requirements for reliability and the specific environmental needs of the control equipment, is generally appropriate.

Battery Rooms

Battery rooms should be maintained between approximately 70 and 80°F for optimum battery capacity and service life. Temperature variations are acceptable as long as they are accounted for in battery sizing calculations. The minimum room design temperature should be taken into account in determining battery capacity. Batteries produce hydrogen gas during charging, so the HVAC system must be designed to limit the hydrogen concentration to the lowest of the levels specified by IEEE *Standard* 484, ASHRAE guidelines, OSHA, and the lower explosive limit (LEL). The recommended hydrogen concentration in the battery room is 2% or less of the room volume. If battery design information is not available, it is recommended that a five air changes per hour be provided for the exhaust system.

TURBINE LUBRICATING OIL STORAGE

A typical power plant has a turbine lubricating oil storage tank and associated filtration equipment. If this storage area is inside the building, the tank should be vented to the outdoors or ventilation rates should provide for dilution of oil fumes. The ventilation systems should be coordinated with fire protection systems to ensure adequate fire suppressant concentration and to prevent spread of fire.

OIL STORAGE AND PUMP BUILDINGS

At a power plant, fuel oil may be the main source of energy for the steam generator, combustion turbine, or diesel generator. It may also be a back-up or supplemental fuel. Coal-fueled plants usually use oil or gas as the initial light-off fuel or for operation of an auxiliary steam generator. Auxiliary steam generators provide initial plant warm-up and building heating.

Oil for combustion is generally a light oil such as No. 2 fuel oil or a heavy oil such as No. 6. Light oils can be pumped at normal temperatures, but heavy oils are highly viscous and may need to be heated for pumping. Oils are usually received by rail or truck, transported by pipeline, and stored in tanks.

Enclosures for pumps, valves, heat exchangers, and associated equipment should be heated and ventilated to remove excess heat and to dilute hydrocarbon fumes. Tank ventilation is an integral part of the tank and piping system design, which is separate from the enclosure ventilation design. Fuel oils are classified in NFPA *Standard* 30 as either combustible or flammable, depending on their vapor pressure at the indoor design temperature. Flammable liquids are hazardous; combustible liquids are not.

The design of HVAC systems for areas containing combustible fuels involves following ventilation principles for heat removal and for good air mixing. Ventilation rates should dilute fumes expected from evaporation of spilled or leaking fuel, following ACGIH (2004) guidelines and material safety data sheets (MSDSs) provided by the material manufacturer. For fuel handling confined to piping systems, the expected leakage is nearly zero, so very low fresh air rates are required for ventilation (generally less than 1 air change per hour). If fuel is handled in open containers or hoses, higher rates are prudent.

If the fuel is flammable at temperatures expected in the room, NFPA *Standard* 30 and other safety and building codes should be followed. Electrical systems may need to be classified as hazardous.

COAL CRUSHER AND COAL TRANSPORTATION SYSTEM BUILDINGS

Coal-handling facilities at a power plant receive and prepare coal and then transport it from the initial delivery point to the burners. Intermediate steps in the process may include long- or short-term storage, cleaning, and crushing. Receipt may include barge, rail car, or truck unloading. Storage may be in piles on the ground, underground, or in barns or silos. At the site, the coal is handled by mobile equipment or conveyor systems.

The following general HVAC considerations apply for the types of structures involved.

Potential for Dust Ignition Explosion

Most types of coal readily break down into dust particles when handled or conveyed. The dust can become fine enough and occur in the right particle size distribution and concentration to create a dust explosion. The design engineer should review and apply the referenced NFPA standards and guidelines to determine the dust ignition potential for each ventilation system application.

Ventilation of Conveyor and Crusher Motors in Coal Dust Environment

Heat from motors and process equipment should be removed through ventilation. The options are to use ducted, ventilated motors or to ventilate the building enclosures. Ventilation in enclosures containing coal should keep the velocity below the entrainment velocities of the expected particle sizes. Table 1 in Chapter 12 of the 2005 *ASHRAE Handbook—Fundamentals* has information on settling velocity. Generally, air should be mechanically exhausted to allow ventilation air to enter the building through louvers at low velocities.

Cooling or Ventilation of Electrical and Control Equipment

Electrical and control equipment may be located near coal piles or other coal-handling facilities. Air-conditioned control rooms should be pressurized with filtered outdoor air. Ventilated motor control or switchgear areas should also be pressurized with filtered air. Because of high dust concentrations in coal yards, ordinary filter media have a short life; a solution is to use inertial filters. For air-conditioned areas, inertial filters can be followed by higher-efficiency media filters.

For electrical equipment rooms adjacent to an area with the potential for a dust ignition explosion, NFPA *Standard* 496 should be followed. This standard recommends the flow of clean air away from electrical equipment into the dusty area.

Ventilation of Methane Fumes

Methane and other hydrocarbons are present in coal both as free gas in cracks and voids and as adsorbents within the coal. Although

most of the methane is released from the interstitial coal structure during mining and handling, some methane or other potentially flammable gases may remain in the coal. Thus, flammable concentrations of methane can accumulate when large amounts of coal are stored. The design engineer should identify the potential for methane accumulation when designing for structures associated with silos or coal storage buildings. At the mine or mine mouth, methane gas emission rates as high as 5 ft^3/ton·day are possible; at other locations, the rate is usually less than 1 ft^3/ton·day. Dust collection air exhaust or natural ventilation is often sufficient to prevent the methane level from reaching the 1% explosion limit. The design engineer should apply guidelines from NFPA *Standards* 120, 123, 850, 8503, 8504, and 8505.

Underground Tunnels and Conveyors

Enclosed conveyors are generally of loose construction and require no ventilation. Smoke or gases in underground conveyor tunnels, hoppers, or conveyor transfer points could cause a personnel safety hazard. Ventilation systems should be coordinated with escape route passages to move fresh air from the direction of the egress. Ventilation rates in the range of 2 to 5 air changes per hour are generally appropriate for normal system operation.

Makeup of Dust Collection Air

Coal dust can be controlled by high-velocity air pickup at locations where coal is transferred. The airflow associated with these pickup points may be sufficient to meet the ventilation requirements. Air inlets must be provided. If additional ventilation is needed, the ventilation fan must coordinate with the dust collection system. For heated structures, makeup air may need to be heated.

HEATING/COOLING SYSTEMS

Selection of the heating and cooling systems in a power plant depends on several variables, including the geographical location and orientation of the plant and the type of fuel used. Most plants are ventilated with outdoor air, but it is customary in hot climates to air-condition many plant areas. Steam, hot water, gas, and electricity are alternative heating methods to be evaluated for the most economical choice. Electricity is the primary energy source for general-purpose cooling of various areas of the plant. Areas such as the main control room, office areas, and electrical switchgear/MCC rooms are air-conditioned for continuous human occupancy or for maintaining the operability of the electrical equipment and controls.

Cooling

The cooling source may be either a centrally located system providing chilled water to various area coolers or individual direct-expansion area coolers with either air- or water-cooled condensing units. Selection depends on the layout of the areas to be cooled and the comparative costs of the two options. The condensing system of the water chiller may be cooled with either air or available water from the plant service water system. Air-cooled chillers are used when air near the proposed chiller location is moderately clean and no fly ash or coal dust problem is anticipated. For a water-cooled system, a closed-loop cooling tower is sometimes used if service water is poor or unavailable (e.g., during start-up or plant outages). To protect chillers from fouling and corrosion by the service water, a heat exchanger is sometimes used between the chiller condenser and the service water source. In a power plant with several operating units and individual self-supporting chilled-water systems, the chilled-water systems of each unit are sometimes interconnected to provide back-up and redundancy.

Heating

Heating in various areas of the power plant is usually provided by electric, steam, or hot-water unit heaters or heating coils in air-handling units. In a hot-water distribution system, glycol is usually added into the system for protection against freezing. Because the building's stack effect induces large quantities of infiltration air, heating requirements in the lower levels of the steam generator building may increase when the steam generator is operating. Pressurization fans directing cooler, outside air into the warmer upper elevations of the plant can offset this infiltration. Also, the design engineer may evaluate redistribution of hotter air from higher to lower elevations.

An alternative to heating the open areas of the plant is to use pipeline heat tracing and spot heating at personnel workstations. For this approach, the design engineer should consider all components that may require heat tracing, such as instrument lines, small and large pipes, traps, pumps, tanks, and other surfaces that may be subject to freezing temperatures. Often the large number of components and surfaces to be heat traced and insulated makes this impractical.

Hydroelectric Power Plants

Hydroelectric power plants consist of a dam structure, draft tubes with gates, and turbine generators. The facility may be arranged with the generation components within the dam structure or within structures attached to the dam. HVAC systems should be provided for reliable operation of the mechanical, electrical, and control equipment and office areas.

The system design should consider the geographical location, humidity, degree of automation needed, and potential for flooding. Dams are typically built in remote locations, so the design and arrangement of the equipment, air intakes, and exhaust ports should consider the potential for vandalism. Accordingly, intakes should include security grating or bars, should not provide a line of sight into the structure, and should be constructed of heavy-gage steel to thwart bullets. HVAC equipment should be indoors if practical, or made otherwise inaccessible.

Humidity is a major design consideration. The lake surface and outfall structure create humid outdoor conditions. Outdoor air used for ventilation may introduce humidity into indoor spaces that may cause corrosion of electrical and control equipment. In addition, dam structure and turbine components below the lake water level are usually at temperatures colder than the dew point of the outside air. Introducing unconditioned outdoor air can create a significant amount of condensation on structure and equipment surfaces.

Another consideration of the remote location of hydroelectric plants is that the HVAC systems need to be reliable and able to operate with minimum attention by operating and maintenance personnel. Thus, these systems may require seasonal changeover features and fully automatic functions. System controls should be integrated with the generation plant controls, such as communication of status and alarm of critical functions to an off-site monitoring facility.

HVAC design should consider the maximum and minimum lake water level. Intakes and exhausts should be above the maximum design flooding level. Suction points for cooling water sources should be below the minimum water level.

Because of the potential for introducing outdoor humidity, cooling of equipment areas, such as the turbine generator hall, turbine and wicker gate, and other mechanical equipment areas, should use a minimum amount of ventilation air. When practical, air should be dehumidified mechanically or with coils using cold lake water. Areas with heat-producing equipment such as for stop-log storage generally do not need ventilation air, which may introduce unwanted humidity. To minimize the effect of outdoor air humidity on electrical and control equipment areas, consideration should be given to water-cooled equipment and radiant cooling to cool structural surfaces. Battery

rooms and oil storage areas should be designed for the specific hazards to minimize excessive ventilation rates.

ENERGY RECOVERY

Energy recovery should be considered in any new system design or system upgrade. Considerations in the power plant should include the following:

- **Interfaces with existing plant process systems.** Using waste steam or steam bled from a process stream must consider process system behavior during generating unit start-up, part load, full load, shutdown, and cold standby/shutdown conditions. Any water returned to the boiler steam cycle must consider effects on the generating unit boiler water chemistry/water treatment.
- **Operating environment,** including cross-contamination of clean airstreams from dirty airstreams, dusty environments, and corrosive conditions from substances such as flue gas. For details, see Chapter 44 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment.*
- **Safety,** including issues resulting from the presence of coal dust, flammable gases, etc. Fire codes and insurance underwriters should be consulted for guidance.
- **Control strategies.**
- **Constructability.**
- **Codes, standards, and local rules and regulations.**

Energy recovery systems should be evaluated by economic analysis of life-cycle costs, including

- Initial cost, including equipment and installation cost
- Fuel and station service power cost
- Operating cost savings
- Maintenance cost

Utility economic evaluations should follow the accounting guidelines and requirements as established by the Federal Energy Regulatory Commission (FERC). See Chapter 36 for further information on owing and operating costs.

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CHAPTER 26

NUCLEAR FACILITIES

THE HVAC requirements for facilities using radioactive materials are discussed in this chapter. Such facilities include nuclear power plants, fuel fabrication and processing plants, plutonium processing plants, hospitals, corporate and academic research facilities, and other facilities housing nuclear operations or materials. The information presented here should serve as a guide; however, careful and individual analysis of each facility is required for proper application.

BASIC TECHNOLOGY

Criticality, radiation fields, and regulation are three issues that are more important in the design of nuclear-related HVAC systems than in that of other special HVAC systems.

Criticality. Criticality considerations are unique to nuclear facilities. Criticality is the condition reached when the chain reaction of fissionable material, which produces extreme radiation and heat, becomes self-sustaining. Unexpected or uncontrolled conditions of criticality must be prevented at all cost. In the United States, only a limited number of facilities, including fuel-processing facilities, weapons facilities, naval shipboard reactors, and some national laboratories, handle special nuclear material subject to criticality concerns.

Radiation Fields. All facilities using nuclear materials contain radiation fields. They pose problems of material degradation and personnel exposure. Although material degradation is usually addressed by regulation, it must be considered in all designs. The personnel exposure hazard is more difficult to measure than the amount of material degradation because a radiation field cannot be detected without special instruments. It is the responsibility of the designer and of the end user to monitor radiation fields and limit personnel exposure.

Regulation. In the United States, the Department of Energy (DOE) regulates weapons-related facilities and national laboratories, and the Nuclear Regulatory Commission (NRC) regulates commercial nuclear plants. Other local, state, and federal regulations may also be applicable. For example, meeting an NRC requirement does not relieve the designer or operator of the responsibility of meeting Occupational Safety and Health Administration (OSHA) requirements. The design of an HVAC system to be used near radioactive materials must follow all guidelines set by these agencies and by the local, state, and federal governments.

For facilities outside the United States, a combination of national, local, and possibly some U.S. regulations apply. In Canada, the Canadian National Safety Commission (CNSC), formerly the Atomic Energy Control Board (AECB), is responsible for nuclear regulation, whereas in the United Kingdom, the Nuclear Installations Inspectorate (NII) and the Environment Agency (EA), are involved in issuing operation licenses.

As Low as Reasonably Achievable (ALARA)

ALARA means that all aspects of a nuclear facility are designed to limit worker exposure and discharges to the environment to the minimum amount of radiation that is reasonably achievable. This refers not to meeting legal requirements, but rather to attaining the lowest cost-effective below-legal levels.

Design

HVAC requirements for a facility using or associated with radioactive materials depend on the type of facility and the specific service required. The following are design considerations:

- Physical layout of the HVAC system that minimizes the accumulation of material within piping and ductwork
- Control of the system so that portions can be safely shut down for maintenance and testing or in the case of any event, accident, or natural catastrophe that causes radioactivity to be released
- Modular design for facilities that change operations regularly
- Preservation of confinement integrity to limit the spread of radioactive contamination in the physical plant and surrounding areas

The design basis in nuclear facilities requires that safety-class systems and their components have active control for safe shutdown of the reactor, for mitigating a design basis accident (DBA) and for controlling radiation release to the environment as the result of an accident.

Advanced nuclear steam supply systems (NSSS) are being designed that incorporate more passive control to minimize dependence on mechanical equipment to mitigate the consequences of a DBA.

Normal or Power Design Basis

The normal or power design basis for nuclear power plants covers normal plant operation, including normal operation mode and normal shutdown mode. This design basis imposes no requirements more stringent than those specified for standard indoor conditions.

Safety Design Basis

The safety design basis establishes special requirements necessary for a safe work environment and public protection from exposure to radiation. Any system designated essential or safety related must mitigate the effect of a design basis accident, or natural catastrophe that may result in the release of radioactivity into the surroundings or the plant atmosphere. These safety systems must be

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The preparation of this chapter is assigned to TC 9.2, Industrial Air Conditioning.

operable at all times unless allowed by a limited condition of operation (LCO). The degree to which an HVAC system contributes to safety determines which components must function during and after a DBA or specific combinations of such events as a safe shutdown earthquake (SSE), a tornado, a loss of coolant accident (LOCA), fuel-handling accident (FHA), control rod drop accident (CRDA), main steam line break (MSLB), and loss of off-site electrical power (LOSP). Non-safety-related systems are not credited in any design basis accident and are designed not to adversely affect safety-related systems.

Previously, safety classification of structures, systems, and components (SSC) was based on a deterministic approach, but will be changed to a risk-informed classification and classified as safety-significant (SS) or low safety-significant (LSS), and categorized in four groups. NRC *Regulatory Guide* 1.201 provides information on safety classification of systems, structures and components.

System Redundancy. Systems important to safety must be redundant and single-failure-proofed. Such a failure should not cause a failure in the back-up system. For additional redundancy requirements, refer to the section on Commercial Facilities.

Seismic Qualification. All safety-class components, including equipment, pipe, duct, and conduit, must be seismically qualified by testing or calculation to withstand and perform under the shock and vibration caused by an SSE or an operating-basis earthquake (OBE) (the largest earthquake postulated for the region). This qualification also covers any amplification by the building structure. In addition, any HVAC component that could, if it failed, jeopardize the essential function of a safety-related component, must be seismically qualified or restrained to prevent such failure.

Environmental Qualification. Safety-class components must be environmentally qualified; that is, the useful life of the component in the environment in which it operates must be determined through a program of accelerated aging. Environmental factors such as temperature, humidity, pressure, and cumulative radiation dose must be considered.

Quality Assurance. All designs and components of safety-class systems must comply with the requirements of a quality assurance (QA) program for design control, inspection, documentation, and traceability of material. For U.S. plant designs, refer to Appendix B of Title 10 of the U.S. *Code of Federal Regulations*, Part 50 (10CFR50) or ASME *Standard* NQA-1 for quality assurance program requirements.

Canadian plant designs use two related series of quality assurance standards: CAN3-286.0 and its six daughter standards, plus four standards in the Z299 series. Quality programs in the United Kingdom are based on ISO 9000. For other countries, refer to the applicable national regulations.

Emergency Power. All safety-class systems must have a backup power source such as an emergency diesel generator.

Outdoor Conditions

Chapters 28 and 31 of the 2005 *ASHRAE Handbook—Fundamentals*, the U.S. National Oceanic and Atmospheric Administration, national weather service of the site country, or site meteorology can provide information on outdoor conditions, temperature, humidity, solar load, altitude, and wind.

Nuclear facilities generally consist of heavy structures with high thermal inertia. Time and temperature lag should be considered in determining heat loads. For some applications, such as diesel generator buildings or safety-related pumphouses in nuclear power plants, the 24 h average temperature may be used as a steady-state value. For critical ventilation system design, site meteorological data should be evaluated.

Indoor Conditions

Indoor temperatures are dictated by occupancy, equipment or process requirements, and comfort requirements based on personnel

activities. HVAC system temperatures are dictated by the environmental qualification of the safety-class equipment located in the space and by ambient conditions during the different operating modes of the equipment.

Indoor Pressures

Where control of airflow pattern is required, a specific building or area pressure relative to the outside atmosphere or to adjacent areas must be maintained. The effect of prevailing wind speed and direction, based on site meteorological information, should be considered. For process facilities with pressure zones, the pressure relationships are specified in the section on Confinement Systems.

In facilities where zoning is different from that in process facilities, and in cases where any airborne radioactivity must not spread to rooms within the same zone, this airborne radioactivity must be controlled by airflow.

Airborne Radioactivity

The level of airborne radioactivity within a facility and the amount released to the surroundings must be controlled to meet the requirements of 10CFR20, 10CFR50, 10CFR61, 10CFR100, 10CFR835, and U.S. DOE *Order* P 441.1, or equivalent national regulations of the site country.

Tornado/Missile Protection

Protection from tornados and the objects or missiles launched by wind or other design basis events is normally required to prevent the release of radioactive material to the atmosphere. A tornado passing over a facility causes a sharp drop in ambient pressure. If exposed to this transient pressure, ducts and filter housings could collapse because the pressure inside the structure would still be that of the environment prior to the pressure drop. Protection is usually provided by tornado dampers and missile barriers in all appropriate openings to the outside. Tornado dampers are heavy-duty, low-leakage dampers designed for pressure differences in excess of 3 psi. They are normally considered safety-class and are environmentally and seismically qualified.

Fire Protection

Fire protection for HVAC and filtration systems must comply with applicable requirements of RG 1.189, Appendix R of 10CFR50, and NFPA, UL, and ANSI or equivalent standards of the site country. Design criteria should be developed for all building fire protection systems, including secondary sources, filter plenum protection, fire dampers, and systems for detection/suppression and smoke management. Fire protection systems may consist of a combination of building sprays, hoses and standpipes, and gaseous or foam suppression. The type of fire postulated in the Fire Hazard Analysis (FHA) or equivalent determines which kind of system is used.

A requirement specific to U.S. nuclear commercial facilities is protection of carbon filter plenums and ventilation ductwork. Manually activated water sprays (window nozzles, fog nozzles, or standard dry pipe/wet pipe system spray heads) are usually used for fire suppression in carbon filter plenums.

Heat detectors and fire suppression systems should be considered for special equipment such as glove boxes. Application of the two systems in combination allows the shutdown of one system at a time for repairs, modifications, or maintenance.

In a DOE facility, the exhaust system duct penetrating a fire-rated boundary does not need a fire damper for maintaining the integrity of the boundary if the duct is fire rated. The exhaust duct may be rated at up to two hours by either wrapping, spraying, or enclosing the duct in an approved material and qualifying it by an engineering analysis. Additional design guidance can be obtained from the *Nuclear Air Cleaning Handbook* (DOE-HDBK-1169-2003).

Smoke control criteria can be found in NFPA *Standards* 801, 803, 804, and 901, or equivalent standards of the site country.

SMOKE MANAGEMENT

The design objective for smoke management in a nuclear facility is to protect the plant operators and equipment from internally and externally generated smoke. Smoke management involves (1) use of materials with low smoke-producing characteristics, (2) prevention of smoke movement to areas where operators may be overcome, (3) use of differential pressures to contain smoke to fire areas, (4) smoke venting to permit access to selected areas, and (5) purging to permit access to areas after a fire.

Smoke control may be static, by prevention of smoke movement (NFPA 90A), or it may be dynamic, by controlling building pressure or air velocities (NFPA 92A). Ventilation systems in the affected areas should be shut down to prevent smoke from migrating and overcoming occupants in other areas. Smoke management for an *internal* fire source should allow the plant operator to shut down the reactor in a controlled manner and maintain shutdown condition. Smoke from an *external* fire should be isolated and appropriate measures provided to prevent smoke from entering the main control room envelope. This envelope includes the main control room and other necessary areas such as restrooms, kitchens, and offices. The location of the safe shutdown panels and the pathway to the safe shutdown panel must be such that, in case of abandonment of the main control room because of fire and smoke, safe egress is ensured.

Capabilities should be provided for purging smoke from fire areas to permit reentry into the areas after the fire is isolated and extinguished. Venting may be used to remove heat and smoke at the point of the fire to permit fire fighting and to control pressures generated by fires.

NFPA 90A, 204, and 92A and NUREG 800 SRP Branch Technical Position CMEB 9.5-1 provide guidance for smoke management and discuss the discharge of smoke and corrosive gases.

Control Room Habitability Zone

The HVAC system in a control room is a safety-related system that must fulfill the following requirements during all normal and postulated accident conditions:

- Maintain conditions comfortable to personnel, and ensure that control room equipment functions continuously and complies with its qualification limit
- Protect personnel from exposure to radiation or toxic chemicals, in the event of a design basis accident
- Protect personnel from combustion products emitted from on-site and off-site fires

Additional information may be obtained from the NRC Standard Review Plans, Sections 6.4 and 9.4.1.

Air Filtration

HVAC filtration systems can be designed to remove either radioactive particles or radioactive gaseous iodine from the airstream. They filter potentially contaminated exhaust air prior to discharge to the environment and may also filter potentially contaminated makeup air for power plant control rooms and technical support centers.

The composition of the filter train is dictated by the type and concentration of the contaminant, the process air conditions, and the filtration levels required by the applicable regulations (e.g., NRC *Regulatory Guides* RG 1.52, RG 1.140; ASME AG-1, N509, and 510; 10CFR20, 10CFR100). Filter trains may consist of one or more of the following components: prefilters, high-efficiency particulate air (HEPA) filters, carbon filters (adsorbers), heaters, demisters and associated ductwork, housings, fans, dampers, and instrumentation. For nuclear-safety-related versions of this equipment, the latest edition of ASME AG-1 codifies rules for Materials; Design; Inspection and Testing; Fabrication; Packaging, Shipping, Receiving, Storage, and Handling; and Quality Assurance. Information common to all equipment is compiled in AG-1, Section AA: General Requirements. The AG-1 Code discusses specific rules for each of the major components in separate sections.

For DOE facilities, the *Nuclear Air Cleaning Handbook* (DOE-HDBK-1169-2003) recommends the design of systems and use of major components for nuclear process facilities and laboratories.

Demisters (Mist Eliminators). Demisters are required to protect HEPA and carbon filters if entrained moisture droplets are expected in the airstream. They should be fire resistant. For details, see AG-1, Section FA.

Heaters. Electric heating coils may be used to meet the relative humidity conditions requisite for carbon filters. For safety-class systems, electric heating coils should be connected to the emergency power supply. Interlocks should be provided to prevent heater operation when the exhaust fan is deenergized. For details, see AG-1, Section CA.

Prefilters/Postfilters. Extended-surface filters are selected for the efficiency required by the particular application. AG-1, Table FB-4200-1, lists the average atmospheric dust spot efficiency ranges. ARI 850 provides efficiency tolerances for the various classes. These types of filters are often used as prefilters for HEPA filters to prevent them from being loaded with atmospheric dust and to minimize replacement costs. High-efficiency (90 to 95%) filters are also often used as postfilters downstream of the carbon filter in lieu of downstream HEPAs. For details, see AG-1, Section FB.

European filter standards use efficiency tolerances from EN 779 in place of ARI 850.

HEPA Filters. HEPA filters are used where there is a risk of particulate airborne radioactivity. For details, see AG-1, Sections FC and FK. For DOE sites, the construction and quality assurance testing of HEPA filters are per DOE *Standards* 3020 and 3025.

Carbon Filters. Activated carbon adsorbers are used mainly to remove radioactive iodine in gaseous state. Bed depths are typically 2 or 4 in. Carbon filters have an efficiency of 99.9% for elemental iodine and 95 to 99% for organic iodine, although they lose efficiency as relative humidity increases. For this reason, they are often preceded by a heating element to keep the relative humidity of the entering air below 70%. Nuclear carbon filters can be either tray type (Type II), rechargeable (Type III), or modular (Type IV). For details on each type, see AG-1, Sections FD, FE, and FH. Carbon efficiency is tested in accordance with ASTM D3803-91 (2004) or its latest edition.

Both carbon and HEPA filters may be affected by exposure to paint solvent, chemicals, and fire, and thus should be tested upon exposure.

Design information for ventilation and air-conditioning system design, ductwork, housings, fans, dampers, and instrumentation are contained in AG-1, Sections CA, RA, SA, HA, BA, DA, and IA, respectively.

DEPARTMENT OF ENERGY FACILITIES

The following discussion applies to U.S. National Laboratory facilities. Nonreactor nuclear HVAC systems must be designed in accordance with DOE *Order* O 420.1B. Critical items and systems in plutonium processing facilities are designed to confine radioactive materials under both normal and DBA conditions, as required by 10CFR100.
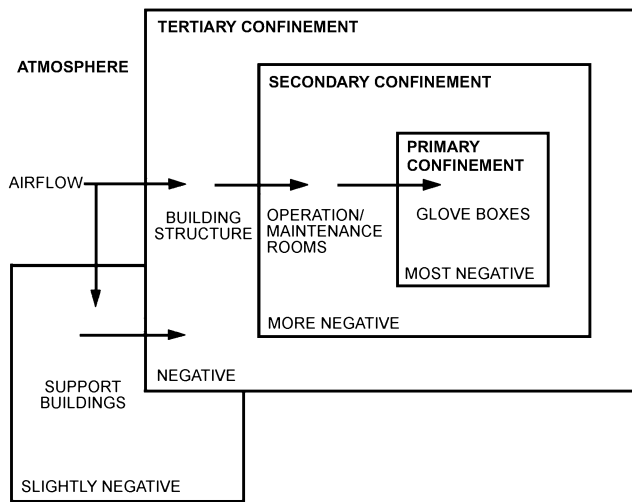
Fig. 1   Typical Process Facility Confinement Categories

CONFINEMENT SYSTEMS

Zoning

Typical process facility confinement systems are shown in Figure 1. Process facilities comprise several zones.

Primary Confinement Zone. This zone includes the interior of the hot cell, canyon, glove box, or other means of containing radioactive material. Containment must prevent the spread of radioactivity within or from the building under both normal conditions and upset conditions up to and including a facility DBA. Complete isolation from neighboring facilities is necessary. Multistage HEPA filtration of the exhaust is required.

Secondary Confinement Zone. This zone is bounded by the walls, floors, roofs, and associated ventilation exhaust systems of the cell or enclosure surrounding the primary confinement zone. Except for glove box operations, this zone is usually unoccupied.

Tertiary Confinement Zone. This zone is bounded by the walls, floors, roofs, and associated ventilation exhaust systems of the facility. They provide a final barrier against the release of hazardous material to the environment. Radiation monitoring may be required at exit points.

Uncontaminated Zone. This zone includes offices and cold shop areas.

Air Locks

Air locks in nuclear facilities are used as safety devices to maintain a negative differential pressure when a confinement zone is accessed. They are used for placing items in primary confinement areas and for personnel entry into secondary and tertiary confinement areas. Administrative controls ensure proper operation of the air lock doors.

There are three methods of ventilating personnel air locks (ventilated vestibules):

- The **clean conditioned supply air** method, where the air lock is at positive pressure with respect to the adjacent zones. For this method to be effective, the air lock must remain uncontaminated at all times.
- The **flow-through ventilation air** method, where no conditioned air is supplied to the air lock and the air lock stays at negative pressure with respect to the less contaminated zone.
- The **combined ventilation air** method, which is a combination of the other two methods. This may be the most effective method, when properly designed.

Zone Pressure Control

Negative static pressure increases (becomes more negative) from the uncontaminated zone to the primary confinement zone, causing any air leakage to be inward, toward areas of higher potential contamination. All zones should be maintained negative with respect to atmospheric pressure. Zone pressure control cannot be achieved through the ventilation system alone; confinement barrier construction must meet all applicable specifications.

Cascade Ventilation

Confinement barriers are enhanced by the use of a cascaded ventilation system, in which pressure gradients cause air to flow from areas of lower contamination to areas of higher contamination through engineered routes. In a cascade ventilation system, air is routed through areas or zones from lower contamination to higher contamination and then to highest contamination, thus reducing the number of separate ventilation systems and the amount of air required for contamination control.

Properly designed air locks should be provided for access between non-contaminated areas and contaminated areas. If there is a potential for development of differential pressure reversal, HEPA filters should be used at the inlet air openings between areas of higher and lower contamination levels to control the spread of contamination into less contaminated or cleaner areas. Appropriate sealing mechanisms should be used for doors or hatches leading into highly contaminated areas.

Differential Pressures

Differential pressures help ensure that air flows in the proper direction in case of a breach in a confinement zone barrier. The design engineer must incorporate the desired magnitudes of the differential pressures into the design early to avoid later operational problems. These magnitudes are normally specified in the design basis document of the safety analysis report (SAR). The following are approximate values for differential pressures between the three confinement zones.

Primary Confinement. With respect to the secondary confinement area, air-ventilated glove boxes are typically maintained at pressures of –0.3 to –1.25 in. of water, inert gas glove boxes at –0.3 to –1.5 in., and canyons and cells at a minimum of –1.0 in.

Secondary Confinement. Differential pressures of –0.03 to –0.15 in. of water with respect to the tertiary confinement area are typical.

Tertiary Confinement. Differential pressures of –0.01 to –0.15 in. of water with respect to the atmosphere are typical.

VENTILATION

Ventilation systems are designed to confine radioactive materials under normal and DBA conditions and to limit radioactive discharges to allowable levels. They ensure that airflows are, under all normal conditions, toward areas (zones) of progressively higher potential radioactive contamination. Air-handling equipment should be sized conservatively so that upsets in the airflow balance do not cause the airflow to reverse direction. Examples of upsets include improper use of an air lock, a credible breach in the confinement barrier, or excessive loading of HEPA filters.

HEPA filters at the ventilation inlets in all primary confinement zone barriers prevent movement of contamination toward zones of lower potential contamination in case of an airflow reversal. Ventilation system balancing helps ensure that the building air pressure is always negative with respect to the outside atmosphere.

Recirculating refers to the reuse of air in a particular zone or area. Room air recirculated from a space or zone may be returned to the primary air-handling unit for reconditioning and then, with the approval of health personnel, be returned to the same space (zone) or to a zone of greater potential contamination. All air recirculated from secondary and tertiary zones must be HEPA-filtered before

reintroduction to the same space. Recirculating air is not permitted in primary confinement areas, except those with inert atmospheres.

A safety analysis is necessary to establish minimum acceptable response requirements for the ventilation system and its components, instruments, and controls under normal, abnormal, and accident conditions.

Analysis determines the number of exhaust filtration stages required in different areas of the facility to limit (in conformance with the applicable standards, policies, and guidelines) the amount of radioactive or toxic material released to the environment during normal and accident conditions. Consult DOE *Orders* O 420.1 and O 430.1 for air-cleaning system criteria.

Ventilation Requirements

A partial recirculating ventilation system may be considered for economic reasons. However, it must be designed to prevent contaminated exhaust from entering the room air-recirculating systems.

The exhaust system is designed to (1) clean radioactive contamination from the discharge air, (2) safely handle combustion products, and (3) maintain the building under negative pressure relative to the outside.

Provisions may be made for independent shutdown of ventilation systems or isolation of portions of the systems to facilitate operations, filter change, maintenance, or emergency procedures such as fire fighting. All possible effects of partial shutdown on the airflows in interfacing ventilation systems should be considered. Positive means must be provided to control the backflow of air that might transport contamination. A HEPA filter installed at the interface between the enclosure and the ventilation system minimizes contamination in the ductwork; a prefilter reduces HEPA filter loading. These HEPA filters should not be considered the first stage of an airborne contamination cleaning system.

Ventilation Systems

The following is a partial list of elements that may be included in the overall air filtration and air-conditioning system:

- Air-sampling devices
- Pre- and/or postfilters (e.g., carbon adsorbers, multiple-bed sand, HEPA)
- Scrubbers
- Demisters
- Process vessel vent systems
- Condensers
- Distribution baffles
- Fire suppression systems
- Fire and smoke dampers
- Exhaust stacks
- Fans
- Coils
- Heat removal systems
- Pressure- and flow-measuring devices
- Duct test ports
- Radiation-measuring devices
- Critically safe drain systems
- Tornado dampers

The ventilation system and associated fire suppression system are designed for fail-safe operation. The ventilation system is equipped with alarms and instruments that report and record its behavior through readouts in control areas and utility service areas.

Control Systems

Control systems for HVAC systems in nuclear facilities have some unique safety-related features. Because the exhaust system is to remain in operation during both normal and accident-related conditions, redundancy in the form of standby fans is often provided. These standby fans and their associated isolation dampers energize

automatically upon a set reduction in either airflow rate or specific location pressure, as applicable. For DOE facilities, maintaining exhaust airflow is important, so fire dampers are excluded from all potentially contaminated exhaust ducts.

Pressure control in the facility interior maintains zones of increasing negative pressure in areas of increasing contamination potential. Care must be taken to prevent wind from unduly affecting the atmospheric control reference. Pulsations can cause the pressure control system to oscillate strongly, resulting in potential reversal of relative pressures. One alternative is to use a variety of balancing and barometric dampers to establish an air balance at the desired differential pressures, lock the dampers in place, and then control the exhaust air to a constant flow rate.

Air and Gaseous Effluents Containing Radioactivity

Air and all other gaseous effluents are exhausted through a ventilation system designed to remove radioactive particulates. Exhaust ducts or stacks located downstream of final filtration that may contain radioactive contaminants should have two monitors, one a continuous air monitor (CAM) and the other a fixed sampler. These monitors may be a combination unit. Exhaust stacks from nuclear facilities are usually equipped with an isokinetic sampling system that relies on a relatively constant airflow rate. The isokinetic sensing probe is a symmetrically arranged series of pickup tubes connected through sweeping bends to a stainless steel header that connects with capillary tubing to a sampling station (CAM). The air velocity through an isokinetic sampling system should be the same as the airstream being sampled. This ensures that particles captured by the isokinetic sampling probe and conveyed to the sampling station are the same size particles that are conveyed in the airstream being sampled. Typically, an exhaust system flow controller modulates the exhaust fan inlet dampers or motor speed to hold the exhaust airflow rate steady while the HEPA filters load.

CAMs can also be located in specific ducts where a potential for radiological contamination has been detected. These CAMs are generally placed beyond the final stage of HEPA filtration, as specified in ANSI *Standard* N13.1. Each monitoring system is connected to an emergency power supply.

The following are design considerations for CAM systems:

- Maintain fully developed turbulent flow at the non-isokinetic sampling point.
- Maintain fully developed laminar flow at the isokinetic sampling point.
- Ensure fully developed turbulent flow is developed between the final filtration and the isokinetic sampling point.
- For accurate CAM operation, heat tracing on the sampling air tubing may be required.
- Maintain the ratio of the sample airflow rate to total discharge airflow rate constant.

COMMERCIAL FACILITIES

NUCLEAR POWER PLANTS

The two kinds of commercial light-water power reactors currently in operation in the United States are the pressurized water reactor (PWR) and the boiling water reactor (BWR). Heavy water (deuterium oxide) reactors are used in Canada and some other countries. Gas-cooled reactors constitute most of the installed base in Great Britain. For all these types, the main objective of the HVAC systems, in addition to ensuring personnel comfort and reliable equipment operation, is protecting operating personnel and the general public from airborne radioactive contamination during normal and accident conditions. Radiation exposure limits are controlled by 10 CFR 20. The "as low as reasonably achievable" (ALARA) concept is the design objective of the HVAC system. The radiological

dose is not allowed to exceed the limits as defined in 10CFR50 and 10CFR100. For other countries operating commercial plants, the specific national rules should be consulted.

NRC Regulatory Guides (RGs) delineate techniques of evaluating specific problems and provide guidance to applicants concerning the information the NRC needs for its review of the facility. The regulatory guides that relate directly to HVAC system design are RG 1.52, RG 1.78, RG 1.140, RG 1.194, RG 1.196, and RG 1.197. Deviations from RG criteria must be justified by the owner and approved by the NRC. Some countries also invoke NRC regulatory guides as part of the design requirements. Deviations from RG criteria must be requested through the applicable government agency in the country of construction.

The design of the HVAC systems for a U.S. nuclear power generating station must ultimately be approved by the NRC staff in accordance with Appendix A of 10CFR50. The NRC developed standard review plans (SRPs) as part of Regulatory Report NUREG-0800 to provide an orderly and thorough review. The SRP provides a good basis or checklist for the preparation of a safety analysis report (SAR). The SRP is the basis for information provided by an applicant in an SAR as required by Section 50.34 of 10CFR50. Technical specifications for nuclear power plant systems are developed by the owner and approved by the NRC as outlined in Section 50.36 of 10CFR50. Technical specifications define the safety limits, limiting conditions for operation (LCO), and surveillance requirements (SR) for all systems important to plant safety.

Minimum requirements for the performance, design, construction, acceptance testing, and quality assurance of equipment used in safety-related air and gas treatment systems in nuclear facilities are found in ASME N509, N510, and AG-1.

Temperature and humidity conditions are dictated by the nuclear steam supply system (NSSS). For U.S. plants, the common modes of operation are normal, hot shutdown, cold shutdown, and refueling.

Normal Operation. NSSS temperature and humidity requirements are specified by the NSSS supplier. Some plants require recirculation filtration trains in the containment building to control the level of airborne contamination. Containment cooling is necessary for maintaining the components in the containment and to ensure that design limits are not exceeded during accidents. Cooling is provided by a containment cooling system.

Refueling Condition. The maximum allowable temperature in the refueling or fuel handling area during refueling is determined by the need to perform refueling safely. Also, because personnel work in protective clothing, they can be vulnerable to heat stress. To prevent this, area cooling can be provided by a normal non-safety-related cooling system. Outdoor air should be provided for ventilation.

Accident Scenarios

Plants are analyzed for four types of accidents: (1) loss of coolant accident (LOCA), (2) fuel handling accident (FHA), (3) control rod drop accident (CRDA), and (4) a main steam line break (MSLB). For all plant types, it necessary to evaluate the limiting accident event and to conduct safety assessments, so measures can be taken to mitigate any accident's any accident's consequences.

Major NSSS Types

Pressurized Water Reactors (PWRs). These reactors, widely used in the United States, use enriched uranium for fuel. The reactor, steam generators, and other components of the NSSS are housed in the containment structure. Other support systems are housed in the auxiliary building, control building, turbine building, and diesel building. In PWR design, the steam turbine is powered by non-radioactive steam for the generation of electricity. General design requirements of the PWR plant are contained in ANSI/ANS *Standard* 56.6-1986.

Boiling Water Reactor (BWRs). Also widely used in the United States, this type of design reactor uses enriched uranium for fuel. The reactor pressure vessel and related piping are housed within the primary containment, which is also referred to as the drywell. The drywell is a low-leakage, pressure-retaining structure designed to withstand the high temperature and pressure from a major break in the reactor coolant line. The drywell is housed within a concrete structure called the secondary containment or the reactor building. Other support systems are housed in the control building, turbine building, and diesel building. In BWR design, the steam turbine is powered by radioactive steam for the generation of electricity. General design requirements of the BWR plant are contained in ANSI/ANS *Standard* 56.7-1987.

Heavy Water Reactors. Canadian power reactors use natural uranium fuel and heavy water (deuterium oxide), which acts as a moderator and a coolant source. The reactor core is mounted in a large, horizontal steel vessel called a calandria, which is enclosed in a concrete containment structure. This design enables the reactors to be refueled while the unit is operating at full power.

Gas-Cooled Reactors. Gas-cooled reactors are primarily used in the United Kingdom. There are two types: Magnox reactors, which use natural uranium metal fuel clad in a magnesium oxide can, and advanced gas-cooled reactors (AGRs), which use slightly enriched uranium oxide fuel in stainless steel with a graphite sleeve.

Russian Reactor Types

VVER Reactors. These are pressurized water reactor systems, similar in many respects to Western PWR designs. A major difference is that the VVER steam generators are horizontal rather than vertical. Besides in Russia, VVER plants are operating in several Eastern European countries and are being built in China and India.

RBMK Reactors. The original Russian reactor design consists of a large graphite block with horizontal pressure tubes similar to the Magnox design. The system is a hybrid of a graphite-moderated and water-cooled design, making the physics of RBMKs very complex.

Commercial Plant License Renewal and Power Uprate

Nuclear power plants were originally licensed for a 40 year term and a defined power output capacity. Most nuclear plants currently operating in the United States have applied for or will be applying for license renewal to extend the plant operating license from 40 to 60 years. As part of the license renewal process, passive plant components, such as HVAC ductwork and piping, are reviewed, and renewal licenses are granted based on the commitment to perform aging management review (AMR) of long-lived components. Credit is taken for the maintenance rule to address upkeep and replacement of active components. Maintenance rule requirements are outlined in 10CFR50.65, Nuclear Energy Institute documents, Nuclear Management Resources Council (NUMARC) 93-0, and NRC Regulatory Guide RG 1.160.

In addition to license renewal, most plants are increasing their power output capacity by as much as 5 to 15% by conducting power uprate evaluations. Power uprates are often done in steps, and are often categorized as (1) measurement uncertainty recapture power uprates, (2) stretch power uprates, and (3) extended-power uprates. As part of the power uprate, the effects of power output on plant and HVAC systems are evaluated, and these systems are upgraded as needed.

Advanced Reactor Systems: New Power Generation Plants

In the United States, it is anticipated that new nuclear power generation plants will be built in the near future, using advanced reactor designs. Most of the advanced reactor designs use a passive cooling system, and the need for safety-related HVAC systems will be minimal.

PLANT HVAC&R SYSTEMS

PRESSURIZED WATER REACTORS

Reactor Containment Building

Containment Cooling. The following systems are typical for containment cooling:

Reactor containment coolers. These units remove most of the heat load. Distribution of the air supply depends on the containment layout and the location of the major heat sources.

Reactor cavity air-handling units or fans. These units are usually transfer fans without coils that provide cool air to the reactor cavity.

Control rod or control element drive mechanism (CRDM or CEDM) air-handling units. The CRDM and CEDM are usually cooled by an induced-draft system using exhaust fans. Because the flow rates, pressure drops, and heat loads are generally high, the air should be cooled before it is returned to the containment atmosphere.

Essential containment cooling units. The containment air-cooling system, or a part of it, is normally designed to provide cooling during normal plant operation and after a postulated accident. The system must be able to perform at high temperature, pressure, humidity, and levels of radioactivity. Cooling coils are provided with essential plant service water.

System design must accommodate both normal and accident conditions. The ductwork must be able to endure the rapid pressure build-up associated with accident conditions, and fan motors must be sized to handle the high-density air.

In addition, the system must be analyzed to identify measures to mitigate the effect of water hammer as addressed in NRC's Generic Letter 96-06.

Radioactivity Control. Airborne radioactivity is controlled by the following means:

Essential air filtration units. Redundant filter units powered by two Class 1E buses are used to reduce the amount of airborne radioactivity. The typical system consists of a demister, a heater, a HEPA filter bank, and a carbon adsorber, possibly followed by a second HEPA filter bank or by a high-efficiency (90 to 95%) filter bank. The electric heater is designed to reduce the relative humidity of the incoming air from 100% to less than 70%. All the components of the air filtration unit are environmentally qualified (EQ), and designed to meet the requirements of a LOCA.

In the case of an accident and the subsequent operation of the filter train, the carbon can become loaded with radioactive iodine such that the decay heat could cause the carbon to self-ignite if the airflow stops. Heat build-up in the carbon adsorber bed should be evaluated, and an appropriate redundant decay heat removal mechanism should be provided.

Containment power access purge or minipurge. Ventilation is sometimes necessary during normal operation, when the reactor is under pressure, to control containment pressure or the level of airborne radioactivity within the containment. The maximum opening size allowed in the containment boundary during normal operation is 8 in.

The system consists of a supply fan, double containment isolation valves in each of the containment wall penetrations (supply and exhaust), and an exhaust filtration unit with a fan. The typical filtration unit contains a HEPA filter and a carbon adsorber, possibly followed by a second HEPA filter or by a high-efficiency (90 to 95%) filter bank. The system is non-safety-related, and operates during personnel access into the containment with the reactor under pressure. During normal plant operation, the containment tends toward positive pressure because of air leaks and the exhaust fan is often operated as needed to control pressure inside the containment.

This **minipurge** system should not be connected to any duct system inside the containment. It should include a debris screen within the containment over the inlet and outlet ducts, so that the containment isolation valves can close even if blocked by debris or collapsed ducts.

Containment refueling purge. Ventilation is required to control the level of airborne radioactivity during refueling. Because the reactor is not under pressure during refueling, there are no restrictions on the size of the penetrations through the containment boundary. Large openings of 42 to 48 in., each protected by double containment isolation valves, may be provided. The required ventilation rate is typically based on 1 air change per hour.

The system consists of a supply air-handling unit, double containment isolation valves at each supply and exhaust containment penetration, and an exhaust fan. Filters are recommended.

Containment combustible gas control. In the case of a LOCA, when a strong solution of sodium hydroxide or boric acid is sprayed into the containment, various metals react and produce hydrogen. Also, if some of the fuel rods are not covered with water, the fuel rod cladding can react with steam at elevated temperatures to release hydrogen into the containment. Therefore, redundant hydrogen recombiners are needed to remove hydrogen from the containment atmosphere, recombine the hydrogen with oxygen, and return the air to the containment. The recombiners may be backed up by special exhaust filtration trains.

BOILING WATER REACTORS

Primary Containment

The primary containment HVAC system consists of recirculating cooling units. It normally recirculates and cools the primary containment air to maintain the environmental conditions specified by the NSSS supplier. During an accident, the system may perform a safety-related function of recirculating the air to prevent stratification of any hydrogen that may be generated if the system is credited in the accident analysis. Depending on the specific plant design, the cooling function may or may not be safety related. Primary containment cooling is necessary for maintaining the life of the components inside the containment and for ensuring that the safety temperature limit of the primary containment is maintained during an accident.

Resistance temperature detectors (RTDs) measure containment temperatures at various locations, and provide input into the volumetric average temperature, which is used as the measure of the containment temperature. The plant's technical specification operating limit is established based on the volumetric average temperature. Temperature problems have been experienced in many BWR primary containments because of temperature stratification and underestimation of heat loads. The cooling system should be designed to adequately mix the air to prevent stratification. Heat load calculations should include a safety factor sufficient to allow for deficiencies and degradation in insulation.

Reactor Building

The reactor building completely encloses the primary containment, auxiliary equipment, and refueling area. Under normal conditions, the reactor building HVAC system maintains the design space conditions and minimizes the release of radioactivity to the environment. The HVAC system consists of a 100% outside air cooling system. Outside air is filtered, heated, or cooled as required before being distributed throughout the various building areas. The exhaust air flows from areas with the least potential contamination to areas of most potential contamination. Before exhausting to the environment, potentially contaminated air is filtered with HEPA filters and carbon adsorbers; all exhaust air is monitored for radioactivity. To ensure that no unmonitored exfiltration occurs during normal operations, the ventilation systems maintain the reactor building at a negative pressure relative to the atmosphere.

During an event involving a LOCA, MSLB, FHA, or high radiation in the ventilation exhaust, the HVAC system's safety-related function is to isolate the secondary containment consisting of the reactor building and the refueling area. Once isolated by fast-closing valves, the secondary containment boundary functions to contain any leakage from the primary containment or refueling area.

Once the secondary containment is isolated, a safety-related standby gas treatment system (SGTS) is started to reduce the ground level releases by drawing down the secondary containment pressure to about –0.25 in. of water within 120 s. The SGTS exhausts air from the secondary containment to the environment at an elevated release location referred to as the main stack. The SGTS consists of redundant filtration trains, which consist primarily of HEPA filters and carbon adsorbers. The capacity of the SGTS is based on the amount of exhaust air needed to reduce the pressure in the secondary containment and maintain it at the design level, given the containment leakage rates and required drawdown times.

In addition to the SGTS, some designs include safety-related recirculating air systems within the secondary containment to mix, cool, and/or treat the air during accidents. These recirculation systems sometimes use portions of the normal ventilation system ductwork; therefore, if the ductwork is used for that purpose, then it must be classified as safety related.

If the isolated secondary containment area is not to be cooled during accidents, it is necessary to determine the maximum temperature that could be reached during an accident. All safety-related components in the secondary containment must be environmentally qualified to operate at that temperature. In most plant designs, safety-related room coolers handle the high heat release with emergency core cooling system (ECCS) pumps.

Turbine Building

Only a BWR supplies radioactive steam directly to the turbine, which could cause a release of airborne radioactivity to the surroundings. Therefore, areas of the BWR turbine building in which release of airborne radioactivity is possible should be enclosed. These areas must be ventilated and the exhaust filtered to ensure that no radioactivity is released to the surrounding atmosphere. Filtration trains typically consist of a prefilter, a HEPA filter, and a carbon adsorber, possibly followed by a second HEPA filter bank or by a high-efficiency (90 to 95%) filter bank. Filtration requirements are based on the plant and site configuration. Depending on outside air conditions at the location, the turbine building is cooled either with outside air or by area coolers served by a chilled-water system.

HEAVY WATER REACTORS

Containment Inlet Air-Conditioning/Exhaust Ventilation System

The production of heavy water in sufficient quantities for the needs of a heavy water reactor is complex and expensive. Once produced, however, deuterium oxide (D_2O) may be reused indefinitely as long as it does not become contaminated. Because heavy water reactor containments are vented and require makeup air, ordinary water (H_2O) is one contaminant that must be contained. This is normally accomplished by means of a non-nuclear safety desiccant air-conditioning unit mounted on the roof of the service building. This unit typically contains a rotary desiccant dryer, hot-water heating coils and chilled-water cooling coils both upstream and downstream of the desiccant wheel, a desiccant regeneration duct containing an electric heater, and a flow control system. The resulting inlet makeup air contains very little moisture. To prevent any radioactive contaminants from escaping up the stack, the containment exhaust ventilation unit typically contains a prefilter bank, a HEPA filter bank, a Type III carbon filter, a second HEPA filter bank, and an exhaust fan.

AREAS OUTSIDE PRIMARY CONTAINMENT

All areas located outside the primary containment are designed to the general requirements contained in ANSI/ANS *Standard* 59.2. These areas are common to any type of plant.

Auxiliary Building

The auxiliary building contains a large amount of support equipment, much of which handles potentially radioactive material. The building may be air conditioned for equipment protection, and the exhaust is filtered to prevent the release of potential airborne radioactivity. The filtration trains typically consist of a prefilter, a HEPA filter, and a carbon adsorber, possibly followed by a second HEPA filter bank or by a high-efficiency (90 to 95%) filter bank.

The HVAC system is a once-through system, as needed for general cooling. Ventilation is augmented by area or room coolers in the individual equipment rooms requiring additional cooling. The building is maintained at negative pressure relative to the outside.

If the equipment in these rooms is not safety related, the area is cooled by normal air-conditioning units. If it is safety related, the area is cooled by safety-related or essential area or room coolers units powered from the same Class 1E (according to IEEE *Standard* 323) power supply as the equipment in the room.

The normal and essential functions may be performed by one unit having both a normal and an essential cooling coil and a safety-related fan served from a Class 1E bus. The normal coil can be a direct-expansion or chilled-water cooling coil served by a normal chilled-water system. The essential coil operates with chilled water from a safety-related chilled-water system or plant service water.

Control Room

The control room HVAC system serves the control room habitability zone (those spaces that must be habitable following a postulated accident to allow orderly shutdown of the reactor) and performs the following functions:

- Controls indoor environmental conditions
- Provides pressurization to prevent infiltration
- Minimizes unfiltered inleakage to that credit in dose assessments
- Protects the zone from hazardous chemical fume intrusion
- Protects the zone from fire
- Removes noxious fumes, such as smoke

In defining the control room envelope or pressure boundary, it is necessary to ensure that, in the event of abandonment as a result of fire or smoke in the control room, access to the remote shutdown panel is safeguarded.

Design requirements for the control room HVAC system are outlined in 10CFR50, GDC 19 Appendix A, Standard Review Plan Sections 6.4 and 9.4.1, NCR *Regulatory Guides* RG 1.52, 1.78, 1.194, 1.196, and 1.197, and NUREG 0737. In 2003, NRC issued Generic Letter 2003-01 to address control room habitability findings at U.S. nuclear power plants, which suggested that licensees may not have been meeting the control room licensing and design basis, and applicable regulatory requirements, and that existing technical specification surveillance requirements may not have been adequate. As a result, all nuclear plants are required to conduct control room inleakage testing using the tracer gas (SF_6) to validate the integrity of the control room boundary and to ensure compliance with dose assessments per GDC 19, Appendix A. It is also necessary to develop and maintain a control room integrity program to control boundary breaches. Plants are also required to conduct assessments of their control room habitability program every three years and inleakage testing every six years. Control room HVAC filter units are designed to filter radioactive contaminants and are fabricated, designed, and tested per ASME *Standards* N509, N510, and AG-1.

Control Cable Spreading Rooms

These rooms are located directly above and below the control room. They are usually served by an independent ventilating or cooling system or by the air-handling units that serve the electric switchgear room or the control room.

Diesel Generator Building

Nuclear power plants have an auxiliary or back-up power source for all essential and safety-related equipment in case of loss of off-site electrical power. The auxiliary power source consists of at least redundant diesel generators, each sized to meet the emergency power load. Heat released by the diesel generator and associated auxiliary systems is normally removed by a safety-related ventilation.

Emergency Electrical Switchgear Rooms

These rooms house the electrical switchgear that controls essential or safety-related equipment. The switchgear located in these rooms must be protected from excessive temperatures (1) to ensure that its qualified life, as determined by environmental qualification, is maintained and (2) to preserve power circuits required for proper operation of the plant, especially its safety-related equipment.

Battery Rooms

Battery rooms should be maintained at approximately 70 to 80°F for optimum battery capacity and service life. Temperature variations are acceptable as long as they are accounted for in battery sizing calculations. The minimum room design temperature should be taken into account in determining battery capacity. Because batteries produce hydrogen gas during charging periods, the HVAC system must be designed to limit the hydrogen concentration to the lowest of the levels specified by IEEE *Standard* 484, ASHRAE guidelines, OSHA, and the lower explosive limit (LEL). The recommended hydrogen concentration (by volume) in the battery room is 2% or less. If battery design information is not available, it is recommended that the exhaust system be designed to provide a minimum of five air changes per hour.

Fuel-Handling Building

New and spent fuel is stored in the fuel-handling building. The building is air conditioned for equipment protection and ventilated with a once-through air system to control potential airborne radioactivity. Normally, the level of airborne radioactivity is so low that the exhaust need not be filtered, although it should be monitored. If significant airborne radioactivity is detected, as can happen during an FHA, the normal building ventilation is isolated and the safety-related system started automatically. The safety-related ventilation system should exhaust through filtration trains powered by Class 1E buses.

Personnel Facilities

For nuclear power plants, these areas usually include decontamination facilities, laboratories, and medical treatment rooms.

Pumphouses

Cooling water pumps are protected by houses that are often ventilated by fans to remove the heat from the pump motors. If the pumps are essential or safety related, the ventilation equipment must also be considered safety related.

Radioactive Waste Building

The building is normally air conditioned for equipment protection and ventilated to control potential airborne radioactivity. The air may require filtration through HEPA filters and/or carbon adsorbers prior to release to the atmosphere.

Technical Support Center

The technical support center (TSC) is an outside facility located close to the control room. Although normally unoccupied, it is used by plant management and technical support personnel during training exercises and accidents.

The TSC HVAC system is designed to provide the same level of comfort (temperature and humidity) and radiological habitability conditions as provided for the control room. The TSC HVAC system is a non-safety-related system, but is augmented to the same level of importance as the main control room HVAC system. An air filtration system (HEPA carbon postfilter) provides the facility protection from radiological releases during an accident. Additional components, such as moisture separators, heaters, and prefilters, are sometimes also used.

GAS-COOLED REACTOR HVAC SYSTEMS

Magnox reactors have a simple HVAC system that provides once-through cooling. Air is drawn from surrounding areas into the space between the biological/thermal shield and the pressure vessel. This cascaded air is routed so as to cool areas of the biological/thermal shield, charge tubes, irradiation tubes, top dome, CO_2 ducting, and other annulus voids. The air is normally extracted with fans and discharged directly to atmosphere without filtration. Carbon filtration to remove radioactive iodine is automatically activated if radioactivity is detected in the exhaust airflow. Other parts of the building, such as the charge hall, discharge well, and turbine hall, have independent supply and exhaust systems.

NONPOWER MEDICAL AND RESEARCH REACTORS

The requirements for HVAC and filtration systems for nuclear nonpower medical and research reactors are set by the NRC. The criteria depend on the type of reactor (ranging from a nonpressurized swimming pool type to a 10 MW or more pressurized reactor), the type of fuel, the degree of fuel enrichment, and the type of facility and environment. Many of the requirements discussed in the sections on various nuclear power plants apply to a certain degree to these reactors. It is therefore imperative for the designer to be familiar with the NRC requirements for the reactor under design.

LABORATORIES

Requirements for HVAC and filtration systems for laboratories using radioactive materials are set by the DOE and/or the NRC. Laboratories located at DOE facilities are governed by DOE regulations. All other laboratories using radioactive materials are regulated by the NRC. Other agencies may be responsible for regulating other toxic and carcinogenic material present in the facility.

Laboratory containment equipment for nuclear processing facilities is treated as a primary, secondary, or tertiary containment zone, depending on the level of radioactivity anticipated for the area and on the materials to be handled. For additional information see Chapter 14, Laboratories.

Glove Boxes

Glove boxes are windowed enclosures equipped with one or more flexible gloves for handling material inside the enclosure from the outside. The gloves, attached to a porthole in the enclosure, seal the enclosure from the surrounding environment. Glove boxes permit hazardous materials to be manipulated without being released to the environment.

Because the glove box is usually used to handle hazardous materials, the exhaust is filtered with a HEPA filter before leaving the box and prior to entering the main exhaust duct. In nuclear processing facilities, a glove box is considered primary confinement

(see Figure 1), and is therefore subject to the regulations governing those areas. For nonnuclear processing facilities, the designer should know the designated application of the glove box and design the system according to the regulations governing that particular application.

Laboratory Fume Hoods

Nuclear laboratory fume hoods are similar to those used in nonnuclear applications. Air velocity across the hood opening must be sufficient to capture and contain all contaminants in the hood. Excessive hood face velocities should be avoided because they cause contaminants to escape when an obstruction (e.g., an operator) is positioned at the hood face. For information on fume hood testing, refer to ASHRAE *Standard* 110.

Radiobenches

A radiobench has the same shape as a glove box except that in lieu of the panel for the gloves, there is an open area. Air velocity across the opening is generally the same as for laboratory hoods. The level of radioactive contamination handled in a radiobench is much lower than that handled in a glove box.

DECOMMISSIONING OF NUCLEAR FACILITIES

The exhaust air filtration system for decontamination and decommissioning (D&D) activities in nuclear facilities depends on the type and level of radioactive material expected to be found during the D&D operations. The exhaust system should be engineered to accommodate the increase in dust loading, with more radioactive contamination than is generally anticipated, because the D&D activities dislodge previously fixed materials, making them airborne. Good housekeeping measures include chemical fixing and vacuuming the D&D area as frequently as necessary.

The following are some design considerations for ventilation systems required to protect the health and safety of the public and the D&D personnel:

- Maintain a higher negative pressure in the areas where D&D activities are being performed than in any of the adjacent areas.
- Provide an adequate capture velocity and transport velocity in the exhaust system from each D&D operation to capture and transport fine dust particles and gases to the exhaust filtration system.
- Exhaust system inlets should be as close to the D&D activity as possible to enhance the capture of contaminated materials and to minimize the amount of ductwork that is contaminated. A movable inlet capability is desirable.
- With portable enclosures, filtration of the enclosure inlet and exhaust air must sustain the correct negative internal pressure.

Low-Level Radioactive Waste

Requirements for the HVAC and filtration systems of low-level radioactive waste facilities are governed by 10 CFR 61. Each facility must have a ventilation system to control airborne radioactivity. The exhaust air is drawn through a filtration system that typically includes a demister, heater, prefilter, HEPA filter, and carbon adsorber, maybe followed by a second filter. Ventilation systems and their CAMs should be designed for the specific characteristics of the facility.

WASTE HANDLING FACILITIES

The handling of radioactive waste requires inventory control of the different radioactive wastes. See the section on Codes and Standards for pertinent publications.

REPROCESSING PLANTS

A reprocessing plant is a specific-purpose facility. Spent nuclear fuel is opened and the contents dissolved in nitric acid to enable the constituents to be chemically separated and recovered. The offgas contains hazardous chemical and radioactive contaminants. Special cleanup equipment, such as condensers, scrubbers, cyclones, mist eliminators, and special filtration, is required to capture the vapors.

CODES AND STANDARDS

ANSI
Standard N13.1   Guide for Sampling Airborne Radioactive Materials in Nuclear Facilities

ANSI/ANS
Standard 56.6-1986   Pressurized Water Reactor Containment Ventilation Systems
Standard 56.7-1987   Boiling Water Reactor Containment Ventilation Systems
Standard 59.2   Safety Criteria for HVAC Systems Located outside Primary Containment

ASME
Standard AG-1   Code on Nuclear Air and Gas Treatment
Standard N509   Nuclear Power Plant Air-Cleaning Units and Components
Standard N510   Testing of Nuclear Air Treatment Systems
Standard NQA-1   Quality Assurance Program Requirements for Nuclear Facility Applications

ANSI/ASHRAE
Standard 110   Method of Testing Performance of Laboratory Fume Hoods
10 CFR   Title 10 of the *Code of Federal Regulations*
Part 20   Standards for Protection Against Radiation (10 CFR 20)
Part 50   Domestic Licensing of Production and Utilization Facilities (10 CFR 50)
Part 61   Land Disposal of Radioactive Waste (10 CFR 61)
Part 65   Requirements for Monitoring the Effectiveness of Maintenance at Nuclear Power Plants
Part 100   Reactor Site Criteria (10 CFR 100)
Part 835   Occupational Radiation Protection (10 CFR 835)

ASTM
Standard 3803-1989   Standard Method for Radioiodine Testing of Nuclear-Grade Gas-Phase Adsorbents

DOE Orders
DOE *Order* O 420.1   Facility Safety
DOE *Order* O 430.1   Life Cycle Asset Management
DOE *Order* P 441.1   Radiological Health and Safety Policy

DOE Standards
DOE *Standard* 3020   Specification for HEPA Filters Used by DOE Contractors
DOE *Standard* 3025   Quality Assurance Inspection and Testing of HEPA Filters
DOE-HDBK-1169-2003   Nuclear Air Cleaning Handbook

ANSI/IEEE
Standard 323   Standard for Qualifying Class 1E Equipment for Nuclear Power Generating Stations

Standard 484   Recommended Practices for Installation Design and Installation of Vented Lead-Acid Batteries for Stationary Applications

NFPA
Standard 90A   Standard for the Installation of Air Conditioning and Ventilating Systems (1999)
Standard 90B   Standard for the Installation of Warm Air Heating and Air Conditioning Systems (1999)
Standard 92A   Recommended practice for smoke control systems (2000)
Standard 204   Standard for Smoke and Heat Venting (2002)
Standard 801   Standard for Facilities Handling Radioactive Materials
Standard 803   Standard for Fire Protection for Light Water Nuclear Power Plants
Standard 804   Standard for Fire Protection for Advanced Light Water Reactor Electric Generating Plants
Standard 901   Classifications for Incident Reporting and Fire Protection Data

ARI
Standard 850   Commercial and Industrial Air Filter Equipment

NRC
NUREG-0696   Functional Criteria for Emergency Response Facilities
NUREG-0737   Clarification of TMI Action Plan Requirements
NUREG-0800   Standard Review Plans
    SRP 6.4   Control Room Habitability Systems
    SRP 9.4.1   Control Room Area Ventilation System
    SRP 9.4.2   Spent Fuel Pool Area Ventilation System
    SRP 9.4.3   Auxiliary and Radwaste Building Ventilation Systems
    SRP 9.4.4   Turbine Area Ventilation System
    SRP 9.4.5   Engineered Safety Feature Ventilation System

NUREG-CR-3786   A Review of Regulatory Requirements Governing Control Room Habitability
Regulatory Guides   U.S. Nuclear Regulatory Commission
    RG 1.52, Rev. 3   Design, Testing, and Maintenance Criteria for Engineered Safety Feature Atmospheric Cleanup System Air Filtration and Adsorption Units of LWR Nuclear Power Plants
    RG 1.78, Rev. 1   Assumptions for Evaluating the Habitability of Nuclear Power Plant Control Room during a Postulated Hazardous Chemical Release
    RG 1.140, Rev. 2   Design, Testing, and Maintenance Criteria for Normal Ventilation Exhaust System Air Filtration and Adsorption Units of LWR Nuclear Power Plants
    RG 1.189   Fire Protection for Operating Nuclear Power Plants
    RG 1.194   Atmospheric Relative Concentrations for Control Room Radiological Habitability Assessments at Nuclear Power Plants
    RG 1.196   Control Room Habitability at Light-Water Nuclear Power Reactors
    RG 1.197   Demonstrating Control Room Envelope Integrity at Nuclear Power Reactors
    RG 1.201   Guidelines for Categorizing Structures, Systems, and Components in Nuclear Power Plants According to Their Safety Significance
Generic Letters
    96-06   Assurance of Equipment Operability and Containment Integrity During Design-Basis Accident Conditions
    2003-01   Control Room Habitability

Canadian Standards
CAN3-N286 Series   Quality Assurance for Nuclear Power Plants
CAN3-Z299   Quality Assurance Programs

European Standards
EN 779   Particulate Air Filters for General Ventilation—Requirements, Testing, Marking

CHAPTER 27

MINE AIR CONDITIONING AND VENTILATION

IN underground mines, excess humidity, high temperatures, inadequate oxygen, and excessive concentrations of dangerous gases can lower worker productivity and can cause illness and death. Air cooling and ventilation are needed in deep underground mines to minimize heat stress and remove contaminants. As mines become deeper, heat removal and ventilation problems become more difficult and costly to solve.

Caution: This chapter presents only a very brief overview of the principles of mine ventilation planning. The person responsible for such planning should either be an experienced engineer, or work under the direct supervision of such an engineer. Seven English-language texts have been written on mine ventilation since 1980 (Bossard 1982; Hall 1981; Hartman et al. 1997; Hemp 1982; Kennedy 1996; McPherson 1993; Tien 1999). The ventilation engineer is strongly encouraged to study these references.

DEFINITIONS

Definitions specific to mine air conditioning and ventilation are as follows.

Heat stress is a qualitative assessment of the work environment based on temperature, humidity, air velocity, and radiant energy. Many heat stress indices have been proposed (see Chapter 8 of the 2005 *ASHRAE Handbook—Fundamentals* for a thorough discussion); the most common in the mining industry are effective temperature (Hartman et al. 1997), air cooling power (Howes and Nixon 1997), and wet-bulb temperature. The following wet-bulb temperature ranges were derived from experience at several deep western U.S. metal mines:

$t_{wb} \leq 80°F$ Worker efficiency 100%

$80 < t_{wb} \leq 85°F$ Economic range for acclimatized workers

$85 < t_{wb} \leq 91°F$ Safety factor range; corrective action required

$91°F < t_{wb}$ Only short-duration work with adequate breaks

Heat strain is the physiological response to heat stress. Effects include sweating, increased heart rate, fatigue, cramps, and progressively worsening illness up to heat stroke. Individuals have different tolerance levels for heat.

Reject temperature, based on the heat stress/strain relationship is the wet-bulb temperature at which air should be rejected to exhaust or recooled. Reject temperature ranges between 78 and 85°F wet bulb, depending on governmental regulation, air velocity, and expected metabolic heat generation rate of workers. Specifying the reject temperature is one of the first steps in planning air-conditioning systems. The ventilation engineer must be able to justify the reject temperature to management because of the economics involved. If too high, work productivity, health, safety, and morale suffer; if too low, capital and operating costs become excessive.

The preparation of this chapter is assigned to TC 9.2, Industrial Air Conditioning.

Critical ventilation depth is the depth at which the air temperature in the intake shaft rises to the reject temperature through autocompression and shaft heat loads. Work areas below the critical ventilation depth rely totally on air conditioning to remove heat. The critical ventilation depth is reached at about 8000 to 10,000 ft, depending on surface climate in the summer, geothermal gradient, and shaft heat loads such as pump systems.

Base heat load is calculated at an infinite airflow at the reject temperature passing through the work area. The temperature of an infinite airflow will not increase as air picks up heat. **Actual heat load** is measured or calculated at the average stope temperature. It is always greater than the base heat load because the average stope temperature is lower than the reject temperature. More heat is drawn from the wall rock. **Marginal heat load** is the difference between base and actual heat loads. It is the penalty paid for using less than an infinite airflow (i.e., the lower the airflow, the lower the inlet temperature required to maintain the reject and the higher the heat load).

Temperature-dependent heat sources (TDHs) depend on the temperature difference between the source and air. Examples include wall rock, broken rock, and fissure water (in a ditch or pipe). **Temperature-independent heat sources (TIHs)** depend only on the energy input to a machine or device after the energy required to raise the potential energy of a substance, if any, is deducted. Examples include electric motors, lights, substation losses, and the calorific value of diesel fuel.

Passive thermal environmental control separates heat sources from ventilating airflows. Examples include insulating pipes and wall rock, and blocking off inactive areas. **Active thermal environmental control** removes heat via airflow and air conditioning quickly enough so that air temperature does not rise above the reject.

Positional efficiency, an important design parameter for mine cooling systems, is the cooling effect reaching the work area divided by the machine evaporator duty. The greater the distance between the machine and work area, the more heat that the cooling medium (air or water) picks up en route.

Percent utilization is the ratio of the evaporator duty of the refrigeration plant over a year in energy units to the duty if the plant had worked the entire year at 100% load. This consideration becomes important when evaluating surface versus underground plants.

Coefficient of performance (COP) usually is defined as the evaporator duty divided by the work of compression in similar units. In mines, the overall COP is used: the evaporator duty divided by all power-consuming devices needed to deliver cooling to the work sites. This includes pumps and fans as well as refrigeration machine compressors.

A **shaft** is a vertical opening or steep incline equipped with skips to hoist the ore, and cages (elevators) to move personnel and supplies. Electric cables and pipes for fresh water, compressed air, cooling water, and pump water are installed in shafts. **Drifts** and **tunnels** are both horizontal openings; a tunnel opens to daylight on both ends, whereas a drift, deep underground, does not. In metal mining, a **stope** is a production site where ore is actually mined. In coal mining, coal is usually produced by either longwall (one continuous production face hundreds of feet long) or room-and-pillar (multiple

production faces in a grid of rooms with supporting pillars in between) methods.

SOURCES OF HEAT ENTERING MINE AIR

Adiabatic Compression

Air descending a shaft increases in pressure (because of the mass of air above it) and temperature. As air flows down a shaft, it increases in temperature as if compressed in a compressor because of conversion of potential energy to internal energy, even if there is no heat interchange with the shaft and no evaporation of moisture.

For dry air at standard conditions (59°F at 14.696 psia), the specific heat at constant pressure c_p is 0.24 Btu/lb·°F. For most work, c_p can be assumed constant, but extreme conditions might warrant a more precise calculation: 1 Btu is added (for descending airflow) or subtracted (for exhaust) to each pound for every 778 ft. The dry-bulb temperature change is $1/(0.24 \times 778 \times 1) = 0.00535$°F per foot, or 1°F per 187 ft of elevation. The specific heat for water vapor is 0.45 Btu/lb·°F. So, for constant air-vapor mixtures, the change in dry-bulb temperature is $(1 + W)/(0.24 + 0.45W)$ per 778 ft of elevation, where W is the humidity ratio in pounds of water per pound of dry air.

The theoretical heat load imposed on intake air by adiabatic compression is given in Equation (1), which is a simplified form of the general energy equation:

$$q = 60Q\rho E \Delta d \qquad (1)$$

where

    q = theoretical heat of autocompression, Btu/h
   60 = 60 min/h
   Q = airflow in shaft, cfm
   ρ = air density, lb/ft^3
   E = energy added per unit distance of elevation change, 1 Btu/778 ft·lb
  Δd = elevation change, ft

Example 1. What is the equivalent heat load from adiabatic compression of 300,000 cfm at 0.070 lb/ft^3 density flowing down a 5000 ft shaft?

  Solution:

$$q = (60)(300,000)(0.070)(1/778)(5000) = 8,097,686 \text{ Btu/h}$$

The adiabatic compression process is seldom truly adiabatic: *autocompression* is a more appropriate term. Other heating or cooling sources, such as shaft wall rock, introduction of groundwater or water sprayed in the shaft to wet the guides, compressed-air and water pipes, or electrical facilities, often mask the effects of adiabatic compression. The actual temperature increase for air descending a shaft usually does not match the theoretical adiabatic temperature increase, for the following reasons:

- The effect of seasonal and daily surface temperature fluctuations, such as cool night air on the rock or shaft lining (rock exhibits thermal inertia, which absorbs and releases heat at different times of the day)
- The temperature gradient of ground rock related to depth
- Evaporation of moisture within the shaft, which suppresses the dry-bulb temperature rise while increasing the moisture content of the air

The wet-bulb temperature lapse rate varies, depending on the entering temperature and humidity ratio, and the pressure drop in the shaft. It averages about 2.5°F wet bulb per 1000 ft, and is much less sensitive to evaporation or condensation than the dry bulb.

Electromechanical Equipment

Electric motors and diesel engines transfer heat to the air. Loss components of substations, electric input to devices such as lights, and all energy used on a horizontal plane appear as heat added to the mine air. Energy expended in pumps, conveyors, and hoists to increase the potential energy of a material does not appear as heat, after losses are deducted.

Vehicles with electric drives, such as scoop-trams, trucks, and electric-hydraulic drill jumbos, release heat into the mine at a rate equivalent to the nameplate and a utilization factor. For example, a 150 hp electric loader operated at 80% of nameplate for 12 h a day liberates (150 hp)(42.4 Btu/min·hp)(0.80) (12 h/day)(60 min/h) = 3,663,360 Btu/day. Dividing by 24 h/day gives an average heat load over the day of 152,640 Btu/h. During the 12 h the loader is operating, the heat load is doubled to 305,280 Btu/h. The dilemma for the ventilation engineer is that, if heat loads are projected at the 152,640 rate, the stope temperature will exceed the reject temperature for half the day, and the stope will be overventilated for the other half; if projected at 305,380 Btu/h, the stope will be greatly overventilated when the loader is not present. Current practice is to accept the additional heat load while the loader is present. Operators get some relief when they leave the heading to dump rock, at which time the ventilation system can partially purge the heading.

Diesel equipment dissipates about 90% of the heat value of the fuel consumed, or 125,000 Btu/gal, to the air as heat (Bossard 1982). The heat flow rate is about three times higher for a diesel engine than for an equivalent electric motor. If the same 150 hp loader discussed previously were diesel-powered, the heat would average about 458,000 Btu/h over the day, and 916,000 Btu/h during actual loader operation. Both sensible and latent heat components of the air are increased because combustion produces water vapor. If a wet scrubber is used, exhaust gases are cooled by adiabatic saturation and the latent heat component increases even further.

Fans raise the air temperature about 0.45°F per in. of water static pressure. Pressures up to 10 in. of water are common in mine ventilation. This is detrimental only when fans are located on the intake side of work areas or circuits.

Groundwater

Transport of heat by groundwater has the largest variance in mine heat loads, ranging from essentially zero to overwhelming values. Groundwater usually has the same temperature as the virgin rock. Ventilating airflows can pick up more heat from hot drain water in an uncovered ditch than from wall rock. Thus, hot drain water should be stopped at its source or contained in pipelines or in covered ditches. Pipelines can be insulated, but the main goal is isolating the hot water so that evaporation cannot occur.

Heat release from open ditches increases in significance as airways age and heat flow from surrounding rock decreases. In one Montana mine, water in an open ditch was 40°F cooler than when it flowed out of the wall rock; the heat was transferred to the air. Evaporation of water from wall rock surfaces lowers the surface temperature of the rock, which increases the temperature gradient of the rock, depresses the dry-bulb temperature of the air, and allows more heat to flow from the rock. Most of this extra heat is expended in evaporation.

Example 2. Water leaks from a rock fissure at 20 gpm and 125°F. If the water enters the shaft sump at 85°F, what is the rate of heat transfer to the air?

  Solution:

  Heat rate $= (20 \text{ gpm})(60 \text{ min/h})(8.33 \text{ lb/gal})(1 \text{ Btu/lb·°F})$
                  $\times (125 - 85 °F) = 399,840 \text{ Btu/h}$

Wall Rock Heat Flow

Wall rock is the main heat source in most deep mines. Temperature at the earth's core has been estimated to be about 10,300°F. Heat flows from the core to the surface at an average of 0.022 Btu/h·ft^2. The implication for mine engineers is that a geothermal gradient exists: rock gets warmer as the mine deepens. The actual gradient varies from approximately 0.5 to over 4°F per 100 ft of depth,

Table 1   Maximum Virgin Rock Temperatures

Mining District	Depth, ft	Temperature, °F
Kolar Gold Field, India	11,000	152
South Africa	12,000	135
Morro Velho, Brazil	8,000	130
North Broken Hill, Australia	3,530	112
Great Britain	4,000	114
Braloroe, BC, Canada	4,100	112.5
Kirkland Lake, Ontario	6,000	81
Falconbridge Mine, Ontario	6,000	84
Lockerby Mine, Ontario	4,000	96
Levac Borehole (Inco), Ontario	10,000	128
Garson Mine, Ontario	5,000	78
Lake Shore Mine, Ontario	6,000	73
Hollinger Mine, Ontario	4,000	58
Creighton Mine, Ontario	10,000	138
Superior, AZ	4,000	140
San Manuel, AZ	4,500	118
Butte, MT	5,200	150
Homestake Mine, SD	8,000	134
Ambrosia Lake, NM	4,000	140
Brunswick #12, New Brunswick, Canada	3,700	73
Belle Island Salt Mine, LA	1,400	88

Source: Fenton (1972).

Table 2   Thermal Properties of Rock Types

Rock Type	Thermal Conductivity, Btu/h·ft·°F	Diffusivity, ft²/h
Coal	1.27	0.050
Gabro	1.37	0.092
Granite	1.11	0.129
Pyritic shale	2.11	0.078
Quartzite	3.18	0.090
Sandstone	1.14	0.065
Shale	1.38	0.035
Rhyolite	2.00	0.043
Sudbury ore	1.50	0.049
North Idaho metamorphic	2.95	0.109

Source: Mine Ventilation Services Inc., Fresno, CA. Reprinted with permission.

depending on the thermal conductivity of local rock. Table 1 gives depths and maximum **virgin rock temperatures (VRTs)** for various mining districts. Table 2 gives thermal conductivities and diffusivities for rock types commonly found in mining. These two variables are required for wall rock heat flow analysis.

Wall rock heat flow is unsteady-state: it decays with time because of the insulating effect of cooled rock near the rock/air boundary. Equations exist for both cylindrical and planar openings, but this section discusses cylindrical equations (Goch and Patterson 1940). The method can solve for either instantaneous or average heat flux rate. The instantaneous rate is recommended because it is better used for older tunnels or drifts. For newer drifts, a series of instantaneous rates over short time periods is equivalent to the average rate. The Goch and Patterson calculations are easily performed on a computer using the following variables and equations:

$$\text{Fo} = \frac{\alpha\theta}{r^2} \qquad (2)$$

$$\varepsilon = \{1.017 + 0.7288\log_{10}(\text{Fo}) + 0.1459\left[\log_{10}(\text{Fo})\right]^2$$
$$- 0.01572\left[\log_{10}(\text{Fo})\right]^3 - 0.004525\left[\log_{10}(\text{Fo})\right]^4 \qquad (3)$$
$$+ 0.001073\left[\log_{10}(\text{Fo})\right]^5\}^{-1}$$

$$\text{Heat Flux, Btu/h·ft}^2 = \frac{k(t_{vr} - t_a)(\varepsilon)}{r} \qquad (4)$$

$$\text{Total Heat Flow, Btu/h} = (\text{Heat Flux})(L)(P) \qquad (5)$$

where

Fo = Fourier number, dimensionless
k = thermal conductivity of rock, Btu/h·ft·°F
L = length of section, ft
P = perimeter of section, ft
r = radius of circular section, ft, or equivalent radius of rectangular section; $r = (A/\pi)^{1/2}$, where
   A = cross-sectional area of section, ft²
t_a = air dry-bulb temperature, °F
t_{vr} = virgin rock temperature, °F
α = thermal diffusivity of rock (equals $k/\rho c$), ft²/h, where
   ρ = rock density, lb/ft³
   c = heat capacity, Btu/lb·°F
ε = function of Fourier number for instantaneous rate, dimensionless (Whillier and Thorpe 1982)
θ = average age of section, h

Example 3. A 500 ft long section of drift, 12 ft high by 15 ft wide, was driven in quartzite with a VRT of 110°F. The drift was started 20 days before the face was reached, and the face is 1 day old. One design criterion is keeping the average dry-bulb temperature of the air in the drift at 80°F. How much heat will flow into the section?

Solution: From Table 2, the thermal conductivity of quartzite is 3.18 Btu/h·ft·°F and the diffusivity is 0.090 ft²/h. The average age of the section is $(20 + 1 \text{ days})/2 = 10.5$ days, or 252 h. The cross-sectional area of the drift is $12 \times 15 = 180$ ft² and the perimeter is $(12 + 15) \times 2 = 54$ ft. The equivalent radius of the drift is $(180/\pi)^{1/2} = 7.57$ ft. The following equations are then applied:

Using Equation (2), $\text{Fo} = \dfrac{\alpha\theta}{r^2} = \dfrac{(0.090)(252)}{7.57^2} = 0.396$

Using Equation (3), $\varepsilon = 1.336$

Using Equation (4),

$$\text{Heat Flux} = \frac{k(t_{vr} - t_a)(\varepsilon)}{r} = \frac{(3.18)(110 - 80)(1.336)}{7.57}$$
$$= 16.84 \text{ Btu/h·ft}^2$$

Using Equation (5),

$$\text{Total Heat Flow} = (\text{Heat Flux})(L)(P)$$
$$= (16.84)(500)(54) = 454,700 \text{ Btu/h}$$

Thus, to keep the average temperature of the drift section at 80°F db, 37.9 tons of refrigeration are needed.

The Goch and Patterson method lacks a convective heat transfer coefficient at the rock/air boundary, and overestimates heat transfer in a dry drift by 8 to 15%. It also does not have a wetness factor. Because a drift with water on the perimeter draws more heat from wall rock, the method underestimates heat flow. Almost all drifts have some wetness on the floor, back, and side walls, though it may not be visible. Comparisons of the Goch and Patterson method with field measurements and results from commercial software under typical conditions (a drift with 20 to 60% of the perimeter wetted) indicate that the overestimate is nearly equal to the underestimate. When using Goch and Patterson for drift heat loads, keep drift section lengths under 200 ft and do not apply any contingency factor to the calculated heat load.

Heat load calculations for stoping require a large number of variables. Irregular shapes, sporadic advance rates, intermittent TIH sources, fissure water, and nonhomogeneous or anisotropic (with directionally differing heat conducting properties) rock are difficult to model (Duckworth and Mousset-Jones 1993; Marks and Shaffner 1993). For cut-and-fill stoping with a sand floor, measured heat

loads are about 70% of the heat loads predicted by Goch and Patterson. Other stoping methods such as room-and-pillar or tabular reef mining are more amenable to planar heat load equations. Patterson (1992) gives empirical graphs relating heat load to productivity and depth.

Ventilation engineers needing to project heat loads for new mines or extensive tunnel projects can write their own computer program using the Goch and Patterson equations, or use a commercial software package. These programs account for convective heat transfer, wetness, elevation changes, and TIH sources that can make hand calculations tedious. However, program input must be carefully derived or the output will be misleading.

Heat from Broken Rock

Freshly blasted broken rock can liberate significant amounts of heat in a confined area. The broken rock's initial and final temperatures, and where the rock is cooled en route from the face to the hoisting facility, must be estimated.

$$\text{Heat, Btu} = (\text{mass})(\text{specific heat})(\text{VRT} - \text{final temperature}) \quad (6)$$

$$\text{Heat load, Btu/h} = \frac{\text{Heat}}{(\text{time, h})} \quad (7)$$

Example 4. A 12 ft high by 15 ft wide by 10 ft long drift round is blasted in quartzite where the VRT is 120°F. Quartzite has a 168 lb/ft^3 density and a 0.2 Btu/lb·°F specific heat. By the time the rock is hoisted to the surface 4 h later, it has cooled to 90°F. What is the heat load imposed on the drift and shaft?

Solution:

$$\text{Heat} = (12 \text{ ft} \times 15 \text{ ft} \times 10 \text{ ft} \times 168 \text{ lb/ft}^3)(0.2 \text{ Btu/lb·°F})$$
$$\times (120 - 90°F) = 1.8144 \times 10^6 \text{ Btu}$$

$$\text{Heat load} = \frac{1.8144 \times 10^6 \text{ Btu}}{4 \text{ h}} = 453,600 \text{ Btu/h}$$

Heat from Other Sources

Heat produced by oxidation of timber and sulfide minerals can be locally significant and even cause mine fires. Fortunately, timber is seldom used for ground support in modern mines. Heat from blasting can also be appreciable. The typical heat potential in various explosives is similar to that of 60% dynamite, about 1800 Btu/lb. This heat is usually swept out of the mine between shifts and thus is not tallied in heat load projections. Body metabolism is only a concern in refuge chambers and is rarely if ever included in heat load projections. Although these heat sources are usually neglected, the ventilation engineer must remain vigilant for cases where local effects might be significant.

Summation of Mine Heat Loads

Mine cooling requirements should be estimated after mining methods, work sites, production rates, and equipment are specified, and heat sources identified. The time frame, during which the ventilation and cooling systems must provide an acceptable work environment, is normally 10 years, but can vary.

Total heat for a mine or mine section is the summation of all TIH and TDH sources. It helps to plot heat sources on a schematic. The heat load from the surface to the entrance of the stope is assessed first, starting with TIH sources because they influence TDH sources. Shaft heat loads, autocompression, and drift heat loads are added to the air en route to stopes. The process should take only one iteration to find a stope entering temperature. Stope heat load is calculated by assuming that the wet bulb leaving the stope equals the design reject temperature. The air temperature entering the stope is estimated, and heat load equations are used to calculate the exit temperature. If this exit temperature exceeds the

reject temperature, a lower stope entering temperature is assumed and a new exit temperature is calculated. The process is repeated with new stope entering temperatures until the calculated stope exit temperature equals the design reject temperature.

If the entering stope temperature calculated from the surface is greater than the entering stope temperature calculated from the reject temperature, higher airflow or air conditioning will be needed. Psychrometrics can determine the size of the airflow increase or cooling required.

HEAT EXCHANGERS

Underground heat exchangers can be water-to-refrigerant, air-to-refrigerant, water-to-water, air-to-water, or air-to-air. Brine can be used instead of water where freezing might occur. Heat exchangers can be direct (e.g., spray chambers) or indirect (e.g., conductive heat transfer through tubes or plates).

See Chapters 16 to 25 and 34 to 44 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment* for general guidelines when designing large cooling plants for mine duty.

Shell-and-Tube and Plate Heat Exchangers

Shell-and-tube heat exchangers are the mainstay of refrigeration machines used in mines. Machines in the 200 to 400 ton range may use either direct expansion (DX) or flooded evaporators. In both cases, the working fluid (refrigerant or water) is circulated through the tubes.

South African mines often use plate-and-frame evaporators in large surface chilled-water plants (van der Walt and van Rensburg 1988). These machines can cool water to within a degree of freezing without danger of rupture. In contrast, shell-and-tube evaporators should not be expected to chill water below 38°F. Manufacturers must be consulted.

Shell-and-tube water-to-water heat exchangers have been used in mine cooling systems to avoid pumping return water against high heads (the U-tube effect). Chilled water from the surface is sent down to the high-pressure (tube) side of the exchanger. Water on the low-pressure side operates district chiller systems or spot coolers. The shell-and-tube water-to-water heat method is not very popular, perhaps because it requires high-pressure supply and return piping. The Second Law of Thermodynamics limits the approach temperature of the outlet high-pressure water to the inlet low-pressure water temperature. This tends to limit heat removal in deep mines that would require at least three heat exchanger stations, in series, in the shaft.

Cooling Coils

Cooling coils can be DX or chilled-water coils. DX coils are used with spot coolers and typically range from 15 to 60 tons. Some modern spot coolers use dual coils in parallel for compactness. Chilled-water coils, used in district chiller systems, are also used in a wide range of sizes.

Air-side fouling is the main operational problem with cooling coils in mines. Coils with fin spacing tighter than 6 fins per inch are not recommended. Water-side fouling is minimal if the water is of fair quality, the circuit is closed, and a corrosion inhibitor is added to the circuit.

Small Spray Chambers

Small spray chambers can be used as an alternative to cooling coils. Heat transfer is direct, air-to-water. Spray chamber maintenance is minimal, and the amount of water sprayed is typically one-half to one-third that required for a cooling coil at the same duty. Some washing effect also occurs in the chamber.

Spray chambers are open systems that dump water into a ditch or collection pond after spraying. This water drains to the dewatering system or is pumped back to the chiller plant. Small spray chambers

are still popular for small duties in mines that chill service water, but the pumping system must be able to handle the increased service water requirement.

Cooling Towers

When heat loads are large, the full capacity of a mine's heat removal system will probably be needed. A key component of the heat removal system is exhaust air. The ventilation engineer for a deep, hot mine must be proficient at designing underground cooling towers for condenser heat rejection, and spray chambers for cooling airflows.

Rather than using the standard HVAC&R method of assessing cooling tower performance, as described in Chapter 36 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*, mining engineers use the South African factor-of-merit method, developed in the 1970s for designing direct-contact heat exchangers (Bluhm 1981; Burrows 1982; Whillier 1977). This method requires a psychrometric program and the following equations:

$$\Sigma = h - (c_{pw})(W)(t) \tag{8}$$

Note that t is either the wet-bulb temperature for air, or the water temperature, depending on whether Σ_{ai} or Σ_{wi} is calculated.

$$q = (M_w)(c_{pw})(t_{wi} - t_{wo}) \tag{9}$$

$$q = (M_a)(\Sigma_{ao} - \Sigma_{ai}) \tag{10}$$

$$n_w = \frac{t_{wi} - t_{wo}}{t_{wi} - t_{ai}} \tag{11}$$

$$R = \frac{(M_w)(c_{pw})(t_{wi} - t_{ai})}{(M_a)(\Sigma_{wi} - \Sigma_{ai})} \tag{12}$$

$$N = \frac{F}{(1 - F)(R^{0.4})} \tag{13}$$

$$n_w = \frac{(1 - e^{-N(1 - R)})}{(1 - Re^{-N(1 - R)})} \text{ (for counterflow towers)} \tag{14}$$

where

a = air
c_{pw} = specific heat of water at constant pressure, 1 Btu/lb·°F
F = factor of merit, roughly equivalent to UA factor in conductive heat transfer, dimensionless; ranges from 0 (no heat transfer) to 1 (as much as heat transfer as allowed by Second Law takes place)
h = enthalpy of moist air, Btu/lb
i = inlet
M = mass flow rate, water or air, lb/min
N = number of transfer units, an intermediate factor for calculating water efficiency
n_w = water efficiency, dimensionless
o = outlet
q = heat rate to be transferred in chamber, Btu/lb
R = tower capacity factor, dimensionless; ratio of heat capacity of water to heat capacity of air under limits of Second Law
t = temperature, °F
W = humidity ratio of moist air, lb water per lb air
w = water
Σ = energy of air, Btu/lb; total enthalpy minus enthalpy of liquid water evaporated into air [approximated by $(c_{pw})(W)(t)$, where t is wet bulb]; dependent only on wet bulb and barometric pressure

Designing an underground cooling tower requires the exhaust air mass flowrate M_a, the wet- and dry-bulb temperatures available at the tower, and the ambient barometric pressure. A psychrometric

program is needed to calculate enthalpy, density, humidity ratio, and specific volume from the wet bulb, dry bulb, and barometric pressure. Tower airflow is taken from measurements or from the mine plan. The temperature, if not measurable (e.g., in a new mine), can be assumed to approach the reject temperature. Experience shows that air usually enters exhaust at about 82 to 83°F wb. Then,

1. Calculate heat rejection rate in the tower (evaporator duty × condenser heat rejection factor, typically between 1.2 and 1.4). Discuss with the manufacturer.
2. Select condenser water flow and use Equation (9) to calculate Δt_w in the tower and machine condensers.
3. Specify cooling tower diameter and tower air velocity.
4. Calculate M_w/M_a.
5. Calculate heat rejection rate per cfm in tower.
6. Calculate air enthalpy h and use Equation (8) to calculate Σ_{ai}.
7. Select a factor of merit for tower using Table 3.
8. Estimate tower capacity factor R (e.g., $R = 0.5$). Using $R = 1$ in Equation (14) will result in division by zero. Skip to Step 10 if $R = 1$, and use the value of F for n_w.
9. Use Equation (13) to calculate N.
10. Use Equation (14) to calculate water efficiency n_w.
11. Use Equation (11) to calculate inlet water temperature t_{wi}.
12. Use Equation (8) to calculate Σ_{wi}, the energy of air at inlet water temperature t_{wi}.
13. Use Equation (12) to calculate a new tower capacity factor R.
14. Compare the R calculated in Step 13 with the R estimated in Step 8. If different by more than 1%, return to Step 8 and re-estimate R. Repeat Steps 9 to 14 until the calculated R is within 1% of the estimated R.
15. Calculate air and water temperatures leaving the tower and the evaporation rate.

Keep the following empirical design criteria in mind during Steps 1 to 5:

- Realistic Δt_w in tower is 12 to 16°F
- Realistic water loading in tower is 6 to 18 gpm per square foot
- Optimum water velocity in machine condenser tubes (3 to 13 fpm, per manufacturer's recommendations) is based on tubing material and water quality
- Realistic maximum air velocity in tower is 1600 fpm
- Realistic ratios of the mass flows of water to air M_w/M_a range from 0.5 to 2.5
- A realistic heat rejection rate in tower is 32 to 65 Btu/h per cfm

Values outside these design parameters are sometimes used (especially when plant duty is increased at a future date), but the penalty paid is a higher condensing temperature and lower COP. Once q, F, M_a, t_{ai}, and M_w are specified, only one t_{wi}, t_{wo}, and t_{ao} will balance all equations.

Example 5. Design a cooling tower for a 1000 ton refrigeration plant planned for a deep, hot mine. Exhaust airflow for heat rejection is

Table 3 Factors of Merit

	Factor of Merit Range	Source
Vertical counterflow, open, unpacked	0.50 to 0.70	Hemp 1982
Horizontal cross-flow		
Single-stage	0.40 to 0.55	Hemp 1982
Two-stage	0.57 to 0.72	Marks 1988
Three-stage	0.69 to 0.81	Marks 1988
Four-stage	0.76 to 0.87	Marks 1988
Commercial packed cooling		
Counterflow tower	0.68 to 0.78	Patterson 1992
Cross-flow tower	0.55 to 0.65	Patterson 1992

250,000 cfm at 83°F saturated. Barometric pressure is 15.226 psia (31 in. of mercury, or 1000 ft below sea level). What size cooling tower is needed, how much condenser cooling water is required, what are the inlet and outlet air and water temperatures, and how much makeup water is needed?

Solution:

Step 1. For a refrigeration plant to produce 1000 tons of cooling, it must reject about 1000 tons × 12,000 Btu/h·ton × 1.25 condenser heat rejection factor = 15,000,000 Btu/h.

Step 2. Select a condenser water flow. For this example, start with 1 gpm per 12,000 Btu/h rejected. The condenser flow is thus 1250 gpm, or 10,413 lb/min at 8.33 lb/gal. The change in water temperature is calculated from Equation (9):

$$\Delta t_w = \frac{15,000,000 \text{ Btu/h}}{(10,413 \text{ lb/min})(60 \text{ min/h})(1 \text{ Btu/lb·°F})} = 24\text{°F}$$

That exceeds the realistic 12 to 16°F Δt_w, so arbitrarily increase the water flow to 2000 gpm and recalculate Δt_w. In practice, selecting the condenser water flow is anything but arbitrary. Generally, the higher the flow, the better, but higher flows require larger condensers to keep tube velocity within design limits, larger cooling towers with more nozzles, and significantly larger pumps. Actual condenser water flow is a compromise between machine and tower performance, capital cost, and overall plant COP (operating cost). At 2000 gpm for this example, $\Delta t_w = 15\text{°F}$, which is acceptable.

Step 3. Specify cooling tower diameter by using a midrange value to 12 gpm/ft^2.

$$(\pi/4)d^2 = \frac{2000 \text{ gpm}}{12 \text{ gpm/ft}^2} \qquad \therefore \quad d = 14.57 \text{ ft} \approx 15 \text{ ft}$$

$$\text{Air velocity} = \frac{250,000 \text{ cfm}}{(\pi/4)(15^2)}$$

$$= 1415 \text{ fpm} \; (< 1600 \text{ fpm; acceptable})$$

Step 4. Calculate M_w/M_a.

$$M_w = (2000 \text{ gpm})(8.33 \text{ lb/gal}) = 16,660 \text{ lb}_w/\text{min}$$

The specific volume for 83°F saturated inlet air at 15.226 psia is 13.71 ft^3/lb$_a$. M_a is therefore

$$M_a = \frac{250,000 \text{ cfm}}{13.71 \text{ ft}^3/\text{lb}_a} = 18,235 \text{ lb}_a/\text{min}$$

$$M_w \S M_a = \frac{16,660}{18,235} = 0.914 \quad (0.5 < M_w/M_a < 2.5; \text{ acceptable})$$

Step 5. The heat rejection rate in the tower is

$$\frac{15,000,000 \text{ Btu/h}}{250,000 \text{ cfm}} = 60 \text{ Btu/h per cfm}$$

This rate is approaching the upper acceptable limit. Consideration should be given to routing more air through the tower if possible. All design criteria have now been met.

Step 6. The enthalpy of air h_{ai} at 83°F saturated and 15.226 psia is 45.95 Btu/lb. $\Sigma_{ai} = 45.95 - (1)(0.0237)(83) = 43.98$ Btu/lb.

Step 7. Select a factor of merit for the tower. From Table 3, an open, unpacked, vertical counterflow cooling tower can conservatively be expected to have a 0.55 factor of merit. If the tower is well designed and actually has a higher factor, the tower will return cooler water to the plant and COP will increase.

Step 8. Estimate $R = 0.5$ (first pass).

Step 9. Calculate N from Equation (13):

$$N = \frac{0.55}{(1 - 0.55)(0.5^{0.4})} = 1.613$$

Step 10. Calculate n_w from Equation (14):

$$n_w = \frac{1 - e^{-1.613(1 - 0.5)}}{1 - 0.5e^{-1.613(1 - 0.5)}} = 0.713$$

Step 11. Calculate t_{wi} from Equation (11) (after manipulation, and assuming that $t_{wi} - t_{wo} = \Delta t_w$):

$$t_{wi} = \frac{\Delta t_w}{n_w} + t_{ai} = \frac{15}{0.713} + 83 = 104.04\text{°F}$$

Step 12. Σ_{wi} at 104.04°F and 15.226 psia = 77.11 − (1)(0.047)(104.04) = 72.22 Btu/lb.

Step 13. Calculate the new R using Equation (12):

$$R = \frac{(16,660)(1)(104.04 - 83)}{(18,235)(72.22 - 43.98)} = 0.681$$

Step 14. The new R is higher than the 0.5 R estimated in Step 8. Return to Step 8 and iterate until the R calculated in Step 13 equals the R projected in Step 8. This occurs at $R = 0.662$.

Step 15. All other values can now be calculated.

$$\text{Per Step 11, } t_{wi} = 106.09\text{°F}$$

$$t_{wo} = 106.09 - 15 = 91.09\text{°F}$$

$$\Sigma_{ao} = \Sigma_{ai} + \frac{15,000,000 \text{ Btu/h}}{(18,235 \text{ lb/min})(60 \text{ min/h})}$$

$$= 43.98 + 13.71 = 57.69 \text{ Btu/lb}$$

$$t_{ao} = 94.5\text{°F (via psychrometric iteration)}$$

The water evaporated in the tower is the difference in humidity ratios ΔW × the mass flow of dry air. From psychrometric equations, $W_{83\text{°F}} = 0.0237 \text{ lb}_w/\text{lb}_a$ and $W_{94.5\text{°F}} = 0.0347 \text{ lb}_w/\text{lb}_a$.

$$\text{Evaporation rate} = (18,235 \text{ lb/min})\frac{0.0347 - 0.0237 \text{ lb}_w/\text{lb}_a}{8.33 \text{ lb}_w/\text{gal}}$$

$$= 24.1 \text{ gpm}$$

Total makeup water depends on evaporation rate, water carryover (if any), and blowdown used to control dissolved solids in the condenser circuit. Leakages and carryover can be deducted from the blowdown. Makeup water is usually planned at 1 to 3% of the condenser water flow, depending on the quality of the makeup water, allowable cycles of concentration of dissolved solids, and water treatment plan.

Vertical unpacked cooling towers in mines often use clog-resistant full-cone nozzles circling the top of the tower, at least 40 ft above the pond. South African mines tend to use ham-type sprayers. Nozzle pressure of 30 psig is typically specified: lower water pressures do not generate the fine water droplets preferred for heat transfer, and higher pressures increase pumping costs. Higher pressures can also impinge water drops into side walls, where the water runs in sheets down the sides. This drastically reduces the surface area of the water flow, which reduces heat transfer. Rings circling the tower are recommended to kick water running down the sides back into the airstream. Unpacked towers do not have as high a factor of merit as towers with film packing or splash bars, but they are virtually maintenance-free and have low resistance to airflow. Figure 1 shows a typical underground vertical counterflow cooling tower.

After a cooling tower begins operation, the actual factor of merit should be determined. This is accomplished by measuring air and water flow rates and temperatures at the tower inlet and outlet, and then working the cooling tower equations in reverse. The actual factor of merit can be used to determine performance at other inlet conditions. This applies to mine, industrial, and commercial cooling towers.

Large Spray Chambers (Bulk Air Coolers)

The procedure for designing spray coolers is the same as for cooling towers, with the following minor changes:

$$q = M_w c_{pw}(t_{wo} - t_{wi}) \tag{15}$$

$$q = M_a(\Sigma_{ai} - \Sigma_{ao}) \tag{16}$$

$$n_w = \frac{1 - e^{-R(1-X)}}{R} \tag{17}$$

where $X = e^N$ for horizontal cross-flow chambers.

A perfect counterflow tower has a factor of merit of 1.0, but the factor of merit for a single cross-flow chamber cannot exceed 0.63 (Bluhm 1981). Two-stage cross-flow chambers are most often specified. Counterflow performance is approximated, and the counterflow equation for water efficiency can be used. Three-stage chambers can be designed when water flow must be limited to control pumping costs. Four-stage chambers are rarely cost-effective in mining applications.

Spray chambers often use vee-jet nozzles at 30 psig, placed uniformly along the chamber length and designed to cover the cross section evenly. Sprays should just reach the back of the chamber. Mist eliminators are usually installed at the chamber exit. Whereas cooling towers need makeup water to replace evaporated water, bulk air coolers gain water through condensation. This water can be sent to the condenser side as makeup. Figure 2 shows a typical two-stage horizontal cross-flow spray chamber.

MINE COOLING TECHNIQUES

A mine cooling system typically sends air, water, or ice into the mine at a low enthalpy state and removes it at a higher one. In hot mines, heat is typically rejected to water being pumped to the surface, and to exhaust air being drawn from the mine. There are many combinations and variations on how this is accomplished. Economics and site-specific conditions determine the optimum methods.
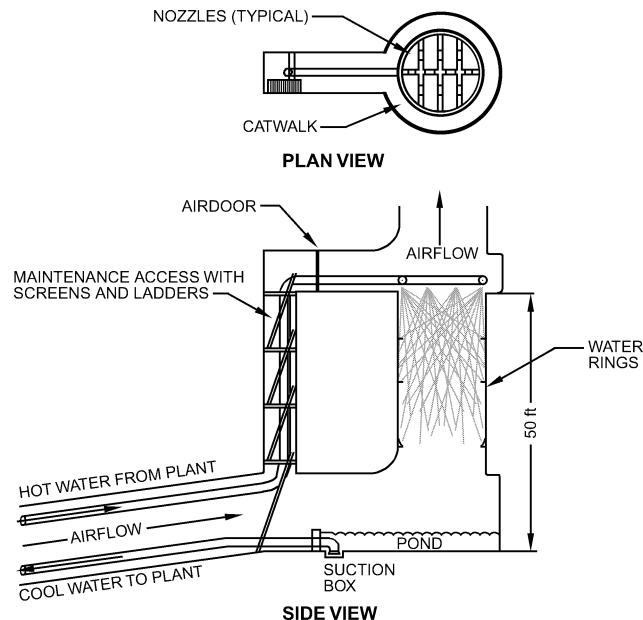
Increasing Airflows

This alternative should be considered first: it is usually less expensive to moderately increase airflows than to install refrigeration if the mine is above the critical ventilation depth. Increasing airflows also helps remove diesel fumes, which is increasingly important for modern mining. However, in deep, usually older mines with small cross-sectional airways, airflow increases may not be practical because of the cube relationship between fan power and airflow increase through a given resistance. Circuit resistance reduction via new airways or stripping existing airways is very expensive.

Chilling Service Water

When a mine requires additional heat removal, and airflow increases are not practical, chilling service water should be considered. Most mining methods require that water be sprayed on rock immediately after blasting to control dust; chilled water can intercept rock heat before the heat escapes into the air. This is a very flexible method of heat removal because it is applied when and where it is needed the most. After blasted rock is removed, the water is turned off and routed elsewhere. Main water lines should be insulated when service water is chilled.

Water is usually chilled in surface plants. A single-pass system is used if regional water supplies are plentiful. If scarce, water is pumped to the surface, recooled, and returned underground. Recycling can ease discharge permit requirements and thus save on treatment costs. Some mines have zero discharge permits. Regions with low winter temperatures and low relative humidities during summer have a natural cooling capacity that is adaptable to water chilling on the surface. Warm mine water is precooled in an evaporative cooling tower before being sent to the refrigeration plant.

Reducing Water Pressure and Energy Recovery Systems

All mines send water underground for drilling, cleaning, suppressing dust, and wetting broken rock. Hot mines using extensive cooling systems often send large volumes of water underground solely for air conditioning. The pressure of descending water must be broken periodically. The most common methods are the open cascade system and pressure-reducing valves. Turbines can also break the pressure and recover a significant portion of the potential energy that would otherwise be lost. Two types of turbines are suitable for mine use: the Pelton wheel, which is most often used, and a centrifugal pump specially designed to run in reverse. The Pelton

Fig. 1   Underground Open Counterflow Cooling Tower
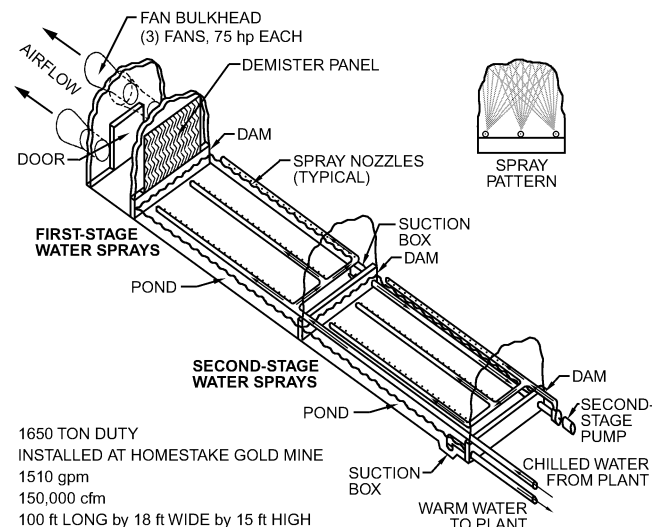
Fig. 2   Two-Stage Horizontal Spray Chamber

wheel rotor is shaped like the spokes of a wheel, with cups attached to the ends of the spokes. One or two nozzles shoot high-pressure water onto the cups, spinning the wheel. It is at least 80% efficient over a range of flows, simply constructed, and readily controlled. A wide operating range is important because water demand fluctuates. A turbine can turn either a generator or pump. Turning a generator is preferred because it separates service and cooling water from the mine dewatering system so that downtime in one system is less likely to disrupt the other.

Besides providing power to help return service water to the surface, turbines have another advantage: unrecovered potential energy is converted to heat at a rate of 1 Btu/lb per 778 ft of depth. If, for example, a 6000 ft deep mine uses 1000 gpm for air conditioning without energy recovery, the water will heat by 7.71°F. If 80% efficient turbines are used, the water temperature rise is about $0.2 \times 7.71 = 1.54$°F. The refrigerating effect lost is only 64 instead of 321 tons.

Other energy-recovery devices include hydrotransformers (large pistons transfer force from the high-pressure side to the lower-pressure side), and three-pipe feeder systems that deliver chilled water on one side while pumping out crushed ore on the other. These concepts have been tested in Europe and South Africa.

Bulk Cooling Versus Spot Cooling

Engineers must balance bulk cooling and spot cooling. **Bulk cooling** using a centrally located plant cools the entire mine, or a large section of it. Benefits are lower cost per ton installed, generally better maintenance, and lower temperatures in non-stoping areas such as haul drifts. Bulk cooling intake air is often done at warm-climate mines to provide winter-like or better conditions year round. Air is cooled in large direct-contact spray chambers adjacent to the shaft and then injected into the shaft below the main landing.

Cooling the entire mine draws more heat from surrounding wall rock, so a larger system must be designed to ensure proper stope cooling (i.e., positional efficiency suffers). When a multilevel mine is bulk cooled, cooling may be wasted on upper levels where heat load is low.

Spot cooling provides adequate temperature control in exploration and development headings, and in stopes on the fringes of mining activity. Total heat load is lower, but cost per ton is higher and temperatures in some areas might exceed design limits.

Combination (Integrated) Surface Systems

Combination (or integrated) systems can cool both air and water. Surface plants devote a higher fraction of cooling capacity to bulk cool intake air in the summer. In winter, a higher fraction is used to chill service or air-conditioning water. Water is delivered underground via open or closed systems, with or without energy recovery. Figure 3 shows components of an integrated mine cooling system.

Underground Refrigeration

Larger refrigeration machines also can be located underground. They usually produce chilled water for cooling air in spray chambers, and heat is rejected to exhaust air via cooling towers. Another method is to operate district cooling systems, using a chiller to produce water for a closed network of cooling coils installed in parallel. These coils can be used in auxiliary systems at individual work areas, or installed in a bank. As with spot coolers, coils should be installed upwind of blasting to limit air-side fouling. Condenser heat from district chiller systems is rejected either to service water or to the mine dewatering system.

Ice Plants

For ultradeep mines (>12,000 ft), or those at the performance limits of existing water and airflow heat rejection systems, ice cooling should be considered. In going from 32 to 90°F before being pumped out of the mine, cooling water starting as ice can remove about 4.5 times the heat as the same mass flow of chilled water in going from 45 to 90°F:

Heat removal (Btu/lb) = Sensible + Latent

Heat removal of chilled water = (1 Btu/lb·°F)(90 − 45) = 45 Btu/lb

Heat removal of ice = (1 Btu/lb·°F)(90 − 32) + 144 Btu/lb = 202 Btu/lb

Heat removal factor increase of ice over water = 202/45 = 4.5

South African mines have been at the forefront in this application (Sheer et al. 2001). Both chunk and slurry delivery methods send ice to underground chambers, where it mixes with warm water returning from the mining area. The cold mixed water is then sent back to the mining area.

Several successful systems have been installed. Cost has dropped as technology improves; the overall COP of ice systems for ultradeep mines is now competitive with traditional cooling methods.

Thermal Storage

This Canadian innovation uses near-surface ice stopes or rock rubble to effectively and inexpensively heat intake air in the winter and cool it in the summer (Stachulak 1989).

Controlled Recirculation

This technique, used in conjunction with bulk air cooling, can reduce ventilation and air-conditioning requirements in older, deep mines, especially heavily mechanized ones (Tien 1999). Besides increasing air velocities in work areas without drawing more surface air through a high-resistance circuit, controlled recirculation reduces the heat load caused by autocompression. Using Equation (1), for every 100,000 cfm at standard density brought from the surface, the lost cooling capacity per 1000 ft of descent is

$$\text{Heat Load} = (100,000 \text{ ft}^3/\text{min})(60 \text{ min/h})(0.075 \text{ lb/ft}^3)$$
$$\times \left(\frac{1 \text{ Btu}}{778 \text{ ft/lb}}\right)(1000 \text{ ft})$$
$$= 578,406 \text{ Btu/h, or } 48.2 \text{ tons of cooling lost}$$
$$\text{per } 100,000 \text{ cfm, per } 1000 \text{ ft}$$
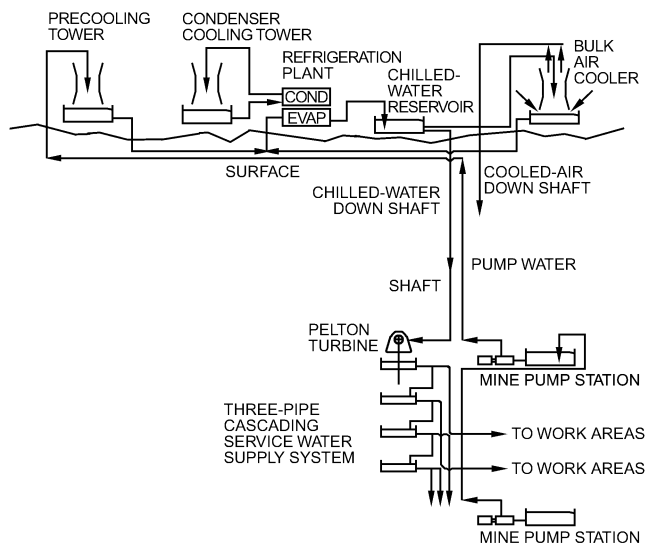
Fig. 3   Integrated Cooling System

Controlled recirculation systems must be designed very carefully, with stringent monitoring and control safeguards.

Cabs and Vests

Mechanization can add significant heat, especially in confined auxiliary-ventilated spaces. Most noncoal mines have converted to diesel equipment in the last 20 years, although some use electric loaders and trucks. Coal mines are also mechanizing, but more slowly. The biggest problem with diesel engine heat is related to the greatest advantage of these vehicles: mobility. Heat and emissions from a diesel vehicle in a confined area can tax almost any ventilation system. Increasingly, cabs are being specified for large diesel vehicles. Cabs come equipped with window-type air conditioners and HEPA filters to capture diesel particulate and dust. After the diesel vehicle has left the heading, the mine ventilation and cooling system can provide an acceptable environment for other personnel. Cabs are expensive; however, because a loader often visits multiple headings in a week, the cost of a cab is much less than maintaining the design reject wet-bulb temperature in all headings at all times.

Cooling vests are not popular in mining. They are bulky, reduce mobility, and are time-consuming to prepare and use. Vests have limited application for mechanics, electricians, pipe-fitters, and others who must enter hot areas to set up ventilation and cooling. Vests using blue-ice packs or dry-ice last two to three hours; those using compressed-air venturi-type coolers require an umbilical cord.

Other Methods

Other methods being developed include the air cycle (air, compressed on the surface and sent underground to a turbine, turns a generator and exits at –40°F), and the ammonia cycle (sending down liquid ammonia, evaporating it, and sending the vapor back to surface condensers). These methods may be best suited to ultradeep mines where other cooling methods are already fully developed.

Transferring heat from current stopes to wall rock or rock rubble in previously worked-out stopes (the only method that does not remove heat from the mine) has also been considered. Refrigeration equipment would have to operate at a high condensing temperature to produce water hot enough to transfer heat to worked-out stopes.

SELECTING A MINE COOLING METHOD

After mine cooling and ventilation requirements have been projected, the designer must analyze and select the best method(s) for meeting those requirements. Cost-benefit analysis is the most widely used, but hardware reliability, dependency on outside factors, flexibility, safety, and technological level are just as important. Some factors to consider include the following:

- **Seasonal ambient conditions.** Warm-climate mines tend to bulk-cool air on the surface in industrial direct-contact spray chambers located close to the intake shaft.
- **Orebody and mining methods.** The more massive the orebody, the more ideal bulk cooling becomes. When stopes are scattered and continuously advanced into new areas, district or spot cooling might be better.
- **Mining rate.** This is critical: heat removal is energy related, not necessarily power related. A fast mining rate prompts a high instantaneous heat load (Btu/h), but less heat energy (Btu) per ton of production. This is because wall rock is covered by fill or isolated before its total heat energy has escaped into the airstream. The Btu per ton of production incurs the air-conditioning costs. Leave as much heat in the wall rock as possible.
- **Size and condition of major airways.** In older mines, small airways often limit airflow increases. This may prompt the need for air conditioning sooner than it normally would have been necessary.
- **Heat sources.** The contribution of TIH and TDH sources to the total can help determine the balance of passive to active thermal

environmental controls, the ratio of airflow to air conditioning, and whether cabs should be specified.

- **Cost of power, water, labor, and supplies.** Knowing these costs is critical for assessing optimum capital expenditure to control operating costs. For example, if power cost is high, spending extra for a higher-COP system may be warranted.
- **Governmental regulations.** Heat stress standards can influence the size of the system. Other safety issues may constrain design, such as not using combustible pipe insulation or ammonia machines underground.

Basic cooling alternatives for specific cases are summarized in Table 4. Airflows are described as limited, medium, or large. One way to express airflow for a given mine is the ratio of tons of airflow per ton of ore. Limited airflow is defined as less than 8 tons of air per ton of ore, medium airflow is 8 to 16 tons per ton, and large airflow is over 16 tons per ton.

These ranges are based on an unpublished study of approximately 100 mines of all types, worldwide. The ranges discussed are for heat removal only. Additional airflow for methane or radon removal must be addressed separately.

MECHANICAL REFRIGERATION PLANTS

Surface Plants

Centrifugal or helical rotary screw machines are typically used in surface plants to chill water or bulk-cool air. Banks of machines are usually installed in parallel: plant design must accommodate one machine being down at any given time for maintenance while others operate. Shell-and-tube heat exchangers are standard, although plate-and-frame are used if water close to the freezing point is specified. The most common refrigerant for positive-displacement compression is HCFC-22. Ammonia is also commonly used in surface plants. Absorption machines can be considered if external waste heat is available.

Table 4 Basic Cooling Alternatives

	Warm Climate	Cool/Cold Climate
Massive ore-body (deep)	Large or medium airflow	Medium airflow
	Chill service water	Chill service water
	Bulk-cool air on surface	Bulk-cool air underground
	Bulk-cool air underground	Thermal storage
Massive ore-body (shallow)	Large airflow	Large or medium airflow
	Bulk-cool air on surface	Chill service water on surface
	Chill service water	
	Shell and tube	Shell and tube
Scattered orebody (multilevel)	Large airflow if not too deep	Large or medium airflow
	Chill service water	Chill service water
	Bulk-cool air on surface	District chiller systems
	District chiller systems	Thermal storage
	Spot coolers/spray chambers	
Ultradeep ore-body (massive and/or multilevel)	Limited airflow	Limited airflow
	Chill service water	Chill service water
	District chiller systems	District chiller systems
	Ice cooling	Ice cooling
	Controlled recirculation	Controlled recirculation
Small orebody	Bulk-cool air on surface	District chiller systems
	Chill service water	Chill service water
	District chiller systems	Spot coolers
	Spot coolers	
Porous rock	District chiller systems	District chiller systems
	Spot coolers	Spot coolers

Underground Plants

Large underground plants do the same work as surface plants, but are closer to work areas. Better positional efficiency and percent utilization are the advantages. Whereas surface plants use atmospheric air for heat rejection, underground plants use mine exhaust air, which raises natural ventilation pressure and aids circuit fans. Components for underground machines must be disassembled for transport down the shaft.

The main disadvantage of underground refrigeration is that heat rejection is limited by the amount of available exhaust air. Excavating underground refrigeration rooms and spray chambers is more costly than erecting prefabricated surface buildings. Maintenance is also more difficult because of shaft logistics. Power is more difficult to supply to an underground facility, and subject to more disruptions.

Spot Coolers

Spot coolers with 15 to 100 ton capacity allow driving long development headings, or cooling exploration sites before installing primary ventilation and cooling equipment. Development headings can be advanced more rapidly and under more comfortable conditions. Condenser heat is most often removed by service water, although some air-to-air condensers are used.

Spot coolers use reciprocating, scroll, or small screw compressors. Hermetic scroll compressors are becoming more popular because they handle liquid slugging better than reciprocating compressors and are less expensive. Spot coolers use direct exchange (DX) air cooling coils. The packaged unit includes a fan, which draws air through the coil (or coils, in a dual-coil unit) and then blows it through duct to the heading. Spot coolers must be compact and portable because they are moved often. The service water required is typically 1.1 gpm per ton, but can be less if the water temperature is under 55°F, or more if it is over 70°F. A return drain pipe is recommended to prevent contact between hot discharge water (often over 100°F) and ambient air. Coils sometimes receive dusty air immediately after blasting; if so, coils must be washed at least every other day.

Spot coolers are expensive, but often are the only choice for cooling exploration, development, and small-scale stoping on the fringes of mining activity.

Maintenance

Mines with extensive systems (e.g., a large chiller plant, or over 10 spot coolers) should employ a mechanic specializing in refrigeration. Mines with over 2000 tons probably need a second mechanic. These persons should be factory-trained and must be certified to handle refrigerants. Refrigeration specialists can be assisted periodically or full-time by apprentice mechanics. Another viable approach is a maintenance contract with the equipment manufacturer or supplier, or an independent HVAC&R shop. Some mines have a full-time person cleaning coils.

A fouling factor (ft^2·h·°F/Btu) should be calculated from lab analysis of the condenser water, especially for district chillers using sump water. Planning a tube-cleaning regimen, either manual, acid circulation, or automatic with brushes and a flow reversal valve, is critical. Underground condensers can become plugged within a couple of weeks without cleaning, depending on the fouling factor. Water treatment is needed to control scale, corrosion, and organisms in surface or underground plants with cooling towers.

MINE AIR HEATING

Cold-climate mines typically heat intake air in the winter. In Canada, heating intake air can cost more than all other ventilation costs combined (Hall 1989). However, without heat, water in the shaft will freeze, disrupting hoisting operations and damaging shaft

support members, cables, and pipes. Very cold air and icy floors are safety and health hazards; heavy gloves and other protective clothing required can make routine tasks difficult. Intake air is typically heated to just above the freezing point. Autocompression and shaft heat loads further temper the air as it downcasts into the mine.

Steam coils operated by boilers burning wood, coal, fuel oil, or natural gas often served as shaft heaters in the past. Electric resistance heaters have also been used, but they are expensive to operate. Waste heat from compressor stations has also been used.

When exhaust and intake shafts are located close together, a circulating glycol or heat pump system can be used to transfer heat from exhaust air to intake. For every degree of total heat (sensible plus latent) given up by warm saturated exhaust air, the same mass flow of cold intake air can be heated sensibly by 4 degrees. Either coils or a cooling tower extracts heat from exhaust air, then coils transfer this heat to the intake air.

Controlled recirculation (up to 25% of total airflow) can also be applied to heat intake air (Hall 1989). The system is temporarily shut down during blasting.

Some cold-climate mines isolate the primary production shaft from the ventilation circuit. A slight upcast flow of uncontaminated air maintains good conditions in the shaft for hoisting ore and moving personnel and supplies. The disadvantage of this method is that ventilation duties of the production shaft must be transferred to one or more expensive stand-alone intake airways.

Natural gas and/or propane heaters are typically used at modern mines. Natural gas is preferred because it is less expensive and it burns more cleanly. Where natural gas is not available, propane must be trucked to the mine site. The same heater can burn either natural gas or propane; thus, propane can be used for back-up in case natural gas is cut off. Direct-fired heaters are usually preferred because the entire heat value of the fuel enters the intake airstream. If indirect heaters are used, roughly 15 to 25% of the heat is lost up the flue pipe.

Two types of natural gas or propane heaters have been used to heat intake air: (1) a grid of burner bars installed in a housing at the intake shaft, sometimes with louvers to adjust the flow of intake air and to mix air from the heaters with outside air; and (2) a crop dryer type of burner. Temperature sensors installed downstream can modulate both heater types to ensure that no more heat is applied than necessary to bring the temperature of the mixed intake air to 34°F.

Carbon monoxide sensors should also be installed downstream of the heaters. Experience at two mines in the western United States shows that the CO content of intake air heated by direct-fired burners can reach 10 to 20 parts per million.

Equation (18) is used to calculate the total heat required, assuming that the air has a low humidity ratio (which is the case for very cold air), and that no water is evaporated in the heater. Heating values for different fuels are given in Table 5.

$$\text{Heat, Btu/h} = (\text{Airflow, cfm})(60 \text{ min/h})(\text{density, lb/ft}^3)$$
$$\times (0.24 \text{ Btu/lb·°F})(\text{D}t, \text{°F}) \tag{18}$$

where Δt = 34°F minus the intake air temperature.

Example 6. A mine is located where the atmospheric air temperature can drop to –20°F for two or more weeks per year. Occasionally the tem-

Table 5   Heating Values for Fuels

Fuel	Value	Source
Natural gas	1000 Btu/ft^3	Kennedy 1996
Propane	90,000 Btu/gal	Kennedy 1996
Bituminous coal	12,300 to 14,400 Btu/lb	Abbeon Cal 2001
Fuel oil	143,000 Btu/gal	Abbeon Cal 2001
Wood	15,000,000 to 31,000,000 Btu/cord	Abbeon Cal 2001

perature drops to –30°F. An intake shaft handles 400,000 cfm, and the density of air entering the shaft in winter is 0.070 lb/ft³. What heating should be installed at the shaft intake to keep the shaft free of ice?

Solution: Sizing heaters is usually based on average cold periods, not extreme cold snaps. Here, a direct-fired heater is sized to raise –20°F air to 34°F. When the temperature drops to –30°F for short periods, intake airflow should be temporarily reduced. Using Equation (18),

Heat = (400,000)(60)(0.070)(0.24)[34 – (–20)] = 21,800,000 Btu/h

If natural gas is used, the volume required is

$$\frac{21,800,000 \text{ Btu/h}}{1000 \text{ Btu/ft}^3} = 21,800 \text{ ft}^3/\text{h}$$

If propane is used, the gallons required are

$$\frac{21,800,000 \text{ Btu/h}}{90,000 \text{ Btu/gal}} = 242 \text{ gal per hour}$$

MINE VENTILATION

Mine ventilation supplies oxygen to underground facilities, and removes dangerous or harmful contaminants such as methane, radon, strata gases, dust, blasting fumes, and diesel emissions. Ventilation also removes heat and helps control humidity in hot mines. Planning a ventilation system consists of five basic steps: (1) determining airflows, (2) planning the primary circuit, (3) specifying circuit fans and their installation, (4) determining auxiliary system requirements, and (5) assessing health and safety aspects.

Determining Airflows

Mining operations generate differing types and amounts of contaminants, and airflows dilute and remove these contaminants. The ventilation engineer must work closely with mine planning staff to understand where and how much production will take place, and what contaminants will be generated. The federal Mine Safety and Health Administration (MSHA) regulates contaminant concentrations to limits specified in the Federal Register, CFR 30. Controlling the most problematic contaminant normally keeps all others within their legal limits. For coal mines, contaminants of concern are typically methane and coal dust; for uranium mines, radon gas; for non-dieselized hard rock mines, usually silica dust and blasting fumes; for dieselized mines, typically diesel emissions. Design airflows for dieselized nonuranium metal mines range from 75 to 150 cfm per diesel horsepower, depending on the reference cited. With the current emphasis on controlling diesel emissions, start planning at 100 cfm per horsepower.

Total airflow is a summation of airflows for individual work areas, plus a leakage factor. Leakage is defined as airflow that does not ventilate any active work area or permanent site such as a pump room. A "tight" system minimizes leakage through well-constructed doors and seals, by minimizing the number of possible leakage paths, and by careful fan placement. Leakage can range from 10% of total airflow at a tight metal mine to 80% at some coal mines.

The ratio of tons of air per ton of ore production is about 2 to 4 for block cave mines, 6 to 8 for nondieselized cut-and-fill metal mines, and 9 to 16 for dieselized metal mines. Gassy coal and uranium mines can have significantly higher ratios, depending on the methane or radon generation rate.

Example 7. A new mechanized cut-and-fill gold mine is planned. Ore production is expected to be 1,200,000 tons per year. Intake air density is 0.070 lb/ft³. What is the rough airflow required for ventilation?

Solution: The airflow range is 9 to 16 tons of air per ton of ore for dieselized metal mines. For a first-pass guess, assume an average 12.5 tons per ton. The total weight of the air through the mine in a year is

$$(1,200,000 \text{ tons ore per year}) \times (12.5 \text{ tons air per ton ore})$$
$$= 15,000,000 \text{ tons air per year}$$

$$\text{Airflow, cfm} = \frac{(15,000,000 \text{ tons/yr})(2000 \text{ lb/ton})}{(0.070 \text{ lb/ft}^3)(525,600 \text{ min/yr})} = 815,400 \text{ cfm}$$

Ratios provide a good first guess. However, the ventilation engineer should derive the total airflow by listing all operations, estimating leakages, and adding the specific airflows required to ventilate each operation (zero-based planning). As with reject temperature, the total airflow selected should be economically justifiable to management.

Airflow specification may change with time because of production, equipment, or mining method changes.

Planning the Circuit

With airflow specified and work sites plotted, the ventilation engineer must lay out the primary circuit. The three basic types of airways are intake, work area, and exhaust. Sizing airways is normally based on keeping velocity within acceptable limits: If velocity is too low, the airway is oversized and thus costs more than necessary; if it is too high, pressure drop is too large and raises operating costs. Air velocity should not exceed 1200 fpm in production shafts and haul drifts. Higher velocities can create dust problems and lead to employee discomfort. However, velocities in bare circular concrete exhaust shafts can approach 5000 fpm if necessary. Air velocity in vertical upcast exhaust shafts should avoid the 1400 to 2300 fpm range because water sheets can form, causing surging at the main fan.

Resistance to airflow is calculated using Atkinson's (1854) and McPherson's (1993) equations:

$$\Delta H = RQ^2 \frac{d}{0.075} \tag{19}$$

where

ΔH = pressure drop, in. of water
R = resistance, in. of water·min²/ft⁶
Q = airflow, cfm
d = actual air density, lb$_m$/ft³
0.075 = standard air density, lb$_m$/ft³

$$R = \frac{kLP}{5.2A^3} \tag{20}$$

where

k = friction factor, lb$_f$·min²/ft⁴ (includes effects of pipes, ground support, and rock surface roughness)
L = length, ft
P = perimeter of opening, ft
5.2 = conversion factor, lb$_f$/ft²·in. of water
A = area of opening, ft²

For rectangular drifts, the k factor can range from 22×10^{-10} for a smooth, concrete-lined straight drift to 90×10^{-10} for an unlined, irregular curved drift. For shafts, the k factor can range from 12×10^{-10} for a smooth-sided borehole to over 500×10^{-10} for a heavily timbered rectangular shaft. See Hartman (1997), McPherson (1993), and Tien (1999) for more precise airway resistance specification.

Example 8. Mine plans call for 65,000 cfm to be sent through 2000 ft of 10 ft wide by 10 ft high drift. The k factor from measurements of similar drifts is 50×10^{-10} lb·min²/ft⁴. The average temperature is 75°F wb and 80°F db. The barometric pressure is 13.8 psia. What is the resistance of this drift, and what is the air pressure drop?

Solution: Using psychrometric equations in Chapter 6 of the 2005 *ASHRAE Handbook—Fundamentals*, the density is 0.0683 lb/ft³.

$$R = \frac{kLP}{5.2A^3} = \frac{(50 \times 10^{-10})(2000)(40)}{(5.2)(100)^3}$$

$$= 7.69 \times 10^{-11} \text{ in. of water} \cdot \text{min}^2/\text{ft}^6$$

$$\Delta H = RQ^2 \frac{d}{0.075} = (7.69 \times 10^{-11})(65,000)^2 \frac{0.0683}{0.075}$$

$$= 0.30 \text{ in. of water}$$

A mine ventilation circuit contains airways in series and in parallel. The overall resistance (Hartman 1997) is

For series: $\quad R_T = R_1 + R_2 + R_3 + \cdots + R_n \qquad (21)$

For parallel: $\quad \dfrac{1}{\sqrt{R_T}} = \dfrac{1}{\sqrt{R_1}} + \dfrac{1}{\sqrt{R_2}} + \dfrac{1}{\sqrt{R_3}} + \cdots + \dfrac{1}{\sqrt{R_n}} \qquad (22)$

Example 9. If Airway #1 has a resistance of 1×10^{-10}, Airway #2 has a resistance of 2×10^{-10}, and Airway #3 has a resistance of 3×10^{-10}, what is the resistance of these three branches in series and in parallel?

Solution:

Series:

$$R_T = 1 \times 10^{-10} + 2 \times 10^{-10} + 3 \times 10^{-10}$$

$$= 6.0 \times 10^{-10} \text{ in. of water} \cdot \text{min}^2/\text{ft}^6$$

Parallel:

$$\frac{1}{\sqrt{R_T}} = \frac{1}{\sqrt{1 \times 10^{-10}}} + \frac{1}{\sqrt{2 \times 10^{-10}}} + \frac{1}{\sqrt{3 \times 10^{-10}}}$$

$$R_T = 1.92 \times 10^{-11} \text{ in. of water} \cdot \text{min}^2/\text{ft}^6$$

Modern ventilation network computer analysis uses Kirchhoff's laws to balance airflows: (1) the summation of airflows into a junction equals the summation out, and (2) the summation of pressure drops around any enclosed mesh equals zero.

Computer simulation allows quick analysis of a wide range of scenarios. Most programs use a balancing algorithm based on the work of Hardy Cross in the 1960s and 1970s. The program iterates as it converges on final balanced airflows. Fan curves or regulators can be inserted in almost any branch.

Regulators or section booster fans control airflow in branches. Without regulation, too little or too much airflow may occur; nevertheless, circuits should be designed with a many free-split branches (branches without a fan or regulator) as possible to minimize overall resistance. Free-split branches are often located in circuit extremities.

A mine should have more intakes than exhausts. This enhances safety, because miners have more escape paths, and because more paths bring in fresh air, in case a fire occurs in one of the intakes. Also, exhaust shafts can generally handle greater air velocities and hence larger quantities, so fewer exhaust shafts are needed.

Metal mines often contain circuit booster fans. Underground boosters can create neutral points in the system where air short-circuits from intake to exhaust above the point, and recirculates from exhaust to intake below the point. Uncontrolled recirculation should be minimized.

Exhausting primary circuits are commonly used in both metal and coal mines (intakes do not have airlocks). Under normal operation, this produces a negative mine pressure gradient. If fans fail or are deactivated, barometric pressure in the mine rises, which temporarily helps keeps methane in coal mines from flowing away from gob (mining waste) areas (Kennedy 1996).

Specifying Circuit Fans

Primary fans are either centrifugal or axial. South African mines typically use large centrifugals, whereas most U.S. and Canadian mines use axials. Both types have advantages. Efficiency (up to 90%) is about the same with either type. Centrifugals are heavier duty, quieter, do not have a pronounced stall region, and can generate higher static pressures (over 30 in. of water). Axials are more compact, and airflows can be easily adjusted by blade angle changes. Primary fans range from 100 to over 3500 hp each. Surface installations with multiple fans are common for large airflows, and for back-up operation when one fan is turned off for maintenance. Circuit fans can also be installed underground, especially in metal mines.

Primary fans are specified while the circuit is designed. Engineers must often balance airway considerations (sizes and numbers) and fan specifications. A fan should be selected that will operate on an efficient part of its curve. Fan speed, quantity, pressure, and power are related in the fan laws equations, described in Chapter 18 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*. Care must also be taken to anticipate future circuit changes as mining operations advance.

The fan installation must be designed after primary fans are selected. Consequences of fan downtime must be carefully considered, especially for coal mines, because methane concentrations can increase when circuit airflows decrease. Fans exhausting a mine are typically mounted horizontally near a vertical shaft or borehole. A 90° transition turns the air into the fan inlet. An isolation door is installed between the transition and fan. Coal mines require a blast door to dampen a shock wave caused by a possible methane or coal dust explosion. An evasé, or diffuser, is attached to the fan outlet to recover part of the velocity pressure exiting the mine. A silencer can be added if surface noise reduction is desired. Increasingly, variable-speed drives are used with electric motors to turn the fans. These drives provide soft start, and speeds from 50 to 100% of synchronous speed, and even to 110% for temporary emergency duty. The installation must be designed for accessibility and ease of maintenance.

Determining Auxiliary System Requirements

Auxiliary fan and duct systems deliver air into dead-end headings. These systems are generally not permitted in coal mines but are common in metal mines. A blowing system is most often used. A fan is set in a fresh air base at the start of a drift, and duct is installed as the drift advances. For drifts under 1000 ft, flexible brattice-cloth duct can be used. Longer drifts that require booster fans need rigid duct because duct gage pressure can drop below atmospheric. Rigid duct also offers less resistance than brattice-cloth duct, but it is about eight times as expensive.

The air quantity needed at the face is determined by the equipment used and the rate at which blasting and diesel fumes must be removed. Ducts are sized for the air quantity needed and for space limitations in the drift. Fans are selected to provide the specified airflow. In general, a single-stage axial fan can generate up to 10 in. of water static pressure, which should deliver required airflow up to 2500 ft through properly sized duct. A larger duct or a two-stage axial fan is needed if distance is much longer. For very long drifts, booster fans are needed about every 2500 ft.

An exhausting system is often used for drifts requiring quick ingress after blasting. Air flows to the face through the drift, captures fumes, and is blown back to the circuit through duct. This keeps the drift clear of fumes. Disadvantages include: (1) the air picks up heat and humidity en route to the face, (2) rigid duct is required, and (3) the face is not swept by air as with a blowing system. A face overlap fan and duct can be installed.

Chapter 35 of the 2005 *ASHRAE Handbook—Fundamentals* provides a friction chart for round duct. However, it is better to acquire the friction chart of the specific duct being considered from the supplier. Shock losses through couplings and bends must be tallied. One important consideration is leakage through couplings. This can be minimized by careful installation, keeping duct pres-

sure under 10 in. of water static pressure, and installing longer pieces of duct (up to 100 ft for brattice cloth, or 20 ft for rigid).

Cassettes loaded with brattice-cloth duct are now used for drifts driven by rapidly advancing tunnel boring machines.

Duct damage is common in mines. Mobile equipment and fly rock from blasting can punch holes in the duct. These factors can drastically reduce airflow. Care must be taken to minimize damage, and to quickly repair or replace damaged pieces.

Assessing Health and Safety

Few aspects of underground mining have as direct an impact on health, safety, and morale as ventilation. No component of ventilation design should be undertaken without a rigorous review of health and safety aspects, including the risk of

- Fire and explosion
- Dangerous and toxic substances
- Heat
- Ventilation equipment usage

For metal mines, fire is the most significant potential ventilation hazard. Fuel, heat, and oxygen are required for combustion; removing any of these components will prevent combustion. Fuel sources such as oil, diesel fuel, and blasting agents are kept in special areas designed to keep out ignition sources. Sprinkler or chemical suppression systems can be installed in these areas as well as in repair shops. Mobile equipment fires are a special concern for modern mining: vehicles should be fitted with a dry chemical fire suppression system, triggered either automatically or by the operator. Electric substation and conveyor fires can be very dangerous.

Engineers should anticipate various scenarios in ventilation circuits. What are the fire risks in any given area? If a fire broke out in any location, how would circuits respond? Would fire-induced natural drafts change airflow quantities and directions? How would fire be detected, how would miners be notified, how would they escape, and how would the fire be fought? MSHA requires that refuge chambers be constructed if miners cannot be hoisted to the surface within 1 h of notification. The ventilation staff must work closely with the safety department and mine management in preplanning how to respond to different emergencies.

Spontaneous combustion is a problem for both metal and coal mines. Fortunately, timber is now seldom used for ground support, although many older mines have worked-out areas that contain timber. Coal, being combustible, can be particularly troublesome. Circuits must be designed so that spontaneous combustion fires will not contaminate active workings.

For coal mines, methane and coal dust explosions pose the greatest risk. Equipment must be rated "permissible," or non-sparking. Airways should be coated with rock dust to prevent a methane ignition from propagating. Methane is explosive in air from 5 to 15% concentration. Whenever methane reaches 0.25%, MSHA requires that changes be made to improve ventilation. At 0.5%, further steps must be taken, and no other work is permitted until the concentration drops. At 1%, all personnel except those working on ventilation must be evacuated from the affected area.

Ventilation is the first line of defense against toxic or asphyxiating gases. These can be generated by blasting (CO, CO_2, NH_3, NO_x) and by diesel engines (CO, NO_x, SO_2, various hydrocarbon compounds, and soot). The rock itself can release CO_2 and H_2S.

The relationship between heat stress and accident frequency has been clearly established in South African mines (Stewart 1982). Work area temperatures should be kept under 85°F wb, especially where heavy physical work is performed.

Ventilation and air-conditioning equipment may also pose health and safety risks. All fan inlets require screens. Fans should be equipped with vibration sensors that can deactivate the fan if neces-

sary. Silencers may be needed if personnel work nearby. Refrigeration rooms must be well ventilated in case of a sudden refrigerant release. Duct, pipe insulation, and other substances such as foam for seals should be approved by MSHA in accordance with 30 CFR Part 7. Electrical systems must meet rigorous MSHA codes.

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CHAPTER 28

INDUSTRIAL DRYING SYSTEMS

DRYING removes water and other liquids from gases, liquids, and solids. The term is most commonly used, however, to describe removing water or solvent from solids by thermal means. **Dehumidification** refers to the drying of a gas, usually by condensation or by absorption with a drying agent (see Chapter 22 of the 2005 *ASHRAE Handbook—Fundamentals*). **Distillation**, particularly **fractional distillation**, is used to dry liquids.

It is cost-effective to separate as much water as possible from a solid using mechanical methods *before* drying using thermal methods. Mechanical methods such as filtration, screening, pressing, centrifuging, or settling require less power and less capital outlay per unit mass of water removed.

This chapter describes industrial drying systems and their advantages, disadvantages, relative energy consumption, and applications.

MECHANISM OF DRYING

When a solid dries, two processes occur simultaneously: (1) the transfer of heat to evaporate the liquid and (2) the transfer of mass as vapor and internal liquid. Factors governing the rate of each process determine the drying rate.

The principal objective in commercial drying is to supply the required heat efficiently. Heat transfer can occur by convection, conduction, radiation, or a combination of these. Industrial dryers differ in their methods of transferring heat to the solid. In general, heat must flow first to the outer surface of the solid and then into the interior. An exception is drying with high-frequency electrical currents, where heat is generated within the solid, producing a higher temperature at the interior than at the surface and causing heat to flow from inside the solid to the outer surfaces.

APPLYING HYGROMETRY TO DRYING

In many applications, recirculating the drying medium improves thermal efficiency. The optimum proportion of recycled air balances the lower heat loss associated with more recirculation against the higher drying rate associated with less recirculation.

Because the humidity of drying air is affected by the recycle ratio, the air humidity throughout the dryer must be analyzed to determine whether the predicted moisture pickup of the air is physically attainable. The maximum ability of air to absorb moisture corresponds to the difference between saturation moisture content at wet-bulb (or adiabatic cooling) temperature and moisture content at supply air dew point. The actual moisture pickup of air is determined by heat and mass transfer rates and is always less than the maximum attainable.

ASHRAE psychrometric charts for normal and high temperatures (No. 1 and No. 3) can be used for most drying calculations. The process will not exactly follow the adiabatic cooling lines because some heat is transferred to the material by direct radiation or by conduction from the metal tray or conveyor.

The preparation of this chapter is assigned to TC 9.2, Industrial Air Conditioning.

Example 1. A dryer has a capacity of 90.5 lb of bone-dry gelatin per hour. Initial moisture content is 228% bone-dry basis, and final moisture content is 32% bone-dry basis. For optimum drying, supply air is at 120°F db and 85°F wb in sufficient quantity that the exhaust air is 100°F db and 84.5°F wb. Makeup air is available at 80°F db and 65°F wb.

Find (1) the required amount of makeup and exhaust air and (2) the percentage of recirculated air.

Solution: In this example, the humidity in each of the three airstreams is fixed; hence, the recycle ratio is also determined. Refer to ASHRAE Psychrometric Chart No. 1 to obtain the humidity ratio of makeup air and exhaust air. To maintain a steady-state condition in the dryer, water evaporated from the material must be carried away by exhaust air. Therefore, the pickup (the difference in humidity ratio between exhaust air and makeup air) is equal to the rate at which water is evaporated from the material divided by the weight of dry air exhausted per hour.

Step 1. From ASHRAE Psychrometric Chart No. 1, the humidity ratios are as follows:

	Dry bulb, °F	Wet bulb, °F	Humidity ratio, lb/lb dry air
Supply air	120	85	0.018
Exhaust air	100	84.3	0.022
Makeup air	80	65.2	0.010

Moisture pickup is $0.022 - 0.010 = 0.012$ lb/lb dry air. The rate of evaporation in the dryer is

$$90.5 (228 - 32)/100 = 177 \text{ lb/h}$$

The dry air required to remove the evaporated water is $177/0.012 = 14{,}750$ lb/h.

Step 2. Assume x = percentage of recirculated air and $(100 - x)$ = percentage of makeup air. Then

Humidity ratio of supply air =
(Humidity ratio of exhaust and recirculated air)$(x/100)$
+ (Humidity ratio of makeup air)$(100 - x)/100$

Hence,

$$0.018 = 0.022(x/100) + 0.010(100 - x)/100$$

x = 66.7% recirculated air
$100 - x$ = 33.3% makeup air

DETERMINING DRYING TIME

The following three methods of finding drying time are listed in order of preference:

- Conduct tests in a laboratory dryer simulating conditions for the commercial machine, or obtain performance data using the commercial machine.
- If the specific material is not available, obtain drying data on similar material by either of the above methods. This is subject to the investigator's experience and judgment.
- Estimate drying time from theoretical equations (see the Bibliography). Care should be taken in using the approximate values obtained by this method.

When designing commercial equipment, tests are conducted in a laboratory dryer that simulates commercial operating conditions. Samples used in the laboratory tests should be identical to the material found in the commercial operation. Results from several tested samples should be compared for consistency. Otherwise, test results may not reflect the drying characteristics of the commercial material accurately.

When laboratory testing is impractical, commercial drying data can be based on the equipment manufacturer's experience.

Commercial Drying Time

When selecting a commercial dryer, the estimated drying time determines what size machine is needed for a given capacity. If the drying time has been derived from laboratory tests, the following should be considered:

- In a laboratory dryer, considerable drying may result from radiation and heat conduction. In a commercial dryer, these factors are usually negligible.
- In a commercial dryer, humidity may be higher than in a laboratory dryer. In drying operations with controlled humidity, this factor can be eliminated by duplicating the commercial humidity condition in the laboratory dryer.
- Operating conditions are not as uniform in a commercial dryer as in a laboratory dryer.
- Because of the small sample used, the test material may not be representative of the commercial material.

Thus, the designer must use experience and judgment to modify the test drying time to suit the commercial conditions.

Dryer Calculations

To estimate preliminary cost for a commercial dryer, the circulating airflow rate, makeup and exhaust airflow rate, and heat balance must be determined.

Circulating Air. The required circulating or supply airflow rate is established by the optimum air velocity relative to the material. This can be obtained from laboratory tests or previous experience, keeping in mind that the air also has an optimum moisture pickup. (See the section on Applying Hygrometry to Drying.)

Makeup and Exhaust Air. The makeup and exhaust airflow rate required for steady-state conditions within the dryer is also discussed in the section on Applying Hygrometry to Drying. In a **continuously operating dryer**, the relationship between moisture content of the material and quantity of makeup air is given by

$$G_T(W_2 - W_1) = M(w_1 - w_2) \qquad (1)$$

where

G_T = dry air supplied as makeup air to the dryer, lb/h
M = stock dried in a continuous dryer, lb/h
W_1 = humidity ratio of entering air, lb water vapor per lb dry air
W_2 = humidity ratio of leaving air, lb water vapor per lb dry air (in a continuously operating dryer, W_2 is constant; in a batch dryer, W_2 varies during part of the cycle)
w_1 = dry basis moisture content of entering material, lb of water per lb
w_2 = dry basis moisture content of leaving material, lb of water per lb

In **batch dryers**, the drying operation is given as

$$G_T(W_2 - W_1) = (M_1)\frac{dw}{d\theta} \qquad (2)$$

where

M_1 = mass of material charged in a discontinuous dryer, lb per batch
$dw/d\theta$ = instantaneous time rate of evaporation corresponding to w

The makeup air quantity is constant and is based on the average evaporation rate. Equation (2) then becomes identical to Equation (1), where $M = M_1/\theta$. Under this condition, humidity in the batch

dryer decreases during the drying cycle, whereas in the continuous dryer, humidity is constant with constant load.

Heat Balance. To estimate the fuel requirements of a dryer, a heat balance consisting of the following is needed:

- Radiation and convection losses from the dryer
- Heating of the commercial dry material to the leaving temperature (usually estimated)
- Vaporization of the water being removed from the material (usually considered to take place at the wet-bulb temperature)
- Heating of the vapor from the wet-bulb temperature in the dryer to the exhaust temperature
- Heating of the total water in the material from the entering temperature to the wet-bulb temperature in the dryer
- Heating of the makeup air from its initial temperature to the exhaust temperature

The energy absorbed must be supplied by the fuel. The selection and design of the heating equipment is an essential part of the overall design of the dryer.

Example 2. Magnesium hydroxide is dried from 82% to 4% moisture content (wet basis) in a continuous conveyor dryer with a fin-drum feed (see Figure 7). The desired production rate is 3000 lb/h. The optimum circulating air temperature for drying is 160°F, which is not limited by the existing steam pressure of the dryer.

Step 1. Laboratory tests indicate the following:

Specific heats

air (c_a)	= 0.24 Btu/lb·°F
material (c_m)	= 0.3 Btu/lb·°F
water (c_w)	= 1.0 Btu/lb·°F
water vapor (c_v)	= 0.45 Btu/lb·°F

Temperature of material entering dryer = 60°F

Temperature of makeup air

dry bulb	= 70°F
wet bulb	= 60°F

Temperature of circulating air

dry bulb	= 160°F
wet bulb	= 100°F

Air velocity through drying bed	= 250 fpm
Dryer bed loading	= 6.82 lb/ft²
Test drying time	= 25 min

Step 2. Previous experience indicates that the commercial drying time is 70% greater than the time obtained in the laboratory test. Thus, the commercial drying time is estimated to be 1.7 × 25 = 42.5 min.

Step 3. The holding capacity of the dryer bed is

3000(42.5/60) = 2125 lb at 4% (wet basis)

The required conveyor area is 2125/6.82 = 312 ft². Assuming the conveyor is 8 ft wide, the length of the drying zone is 312/8 = 39 ft.

Step 4. The amount of water in the material entering the dryer is

3000[82/(100 + 4)] = 2370 lb/h

The amount of water in the material leaving is

3000[4/(100 + 4)] = 115 lb/h

Thus, the moisture removal rate is 2370 − 115 = 2255 lb/h.

Step 5. The air circulates perpendicular to the perforated plate conveyor, so the air volume is the face velocity times the conveyor area:

Air volume = 250 × 312 = 78,000 cfm

ASHRAE Psychrometric Charts 1 and 3 show these air properties:

Supply air (160°F db, 100°F wb)

Humidity ratio	= 0.0285 lb per lb of dry air
Specific volume	= 16.33 ft³ per lb of dry air

Makeup air (70°F db, 60°F wb)

Humidity ratio W_1	= 0.0086 lb per lb of dry air

The mass flow rate of dry air is

(78,000 × 60)/16.33 = 286,500 lb/h

Step 6. The amount of moisture pickup is

$$2255/286,500 = 0.0079 \text{ lb per lb of dry air}$$

The humidity ratio of the exhaust air is

$$W_2 = 0.0285 + 0.0079 = 0.0364 \text{ lb per lb of dry air}$$

Substitute in Equation (1) and calculate G_T as follows:

$$G_T(0.0364 - 0.0086) = (3000/1.04)(82 - 4)/100$$

$$G_T = 81,000 \text{ lb dry air per hour}$$

Therefore,

Makeup air	$= 100 \times 81,000/286,500 = 28.3\%$
Recirculated air	$= 71.7\%$

Step 7. Heat Balance

Sensible heat of material	$=$	$M(t_{m2} - t_{m1})c_m$
	$=$	$(3000/1.04)(100 - 60)0.3$
	$=$	$34,600 \text{ Btu/h}$
Sensible heat of water	$=$	$M_{w1}(t_w - t_{m1})c_w$
	$=$	$2370(100 - 60)1.0$
	$=$	$94,800 \text{ Btu/h}$
Latent heat of evaporation	$=$	$M(w_1 - w_2)H$
	$=$	$2255 \text{ lb/h} \times 1037 \text{ Btu/lb}$
	$=$	$2,338,400 \text{ Btu/h}$
Sensible heat of vapor	$=$	$M(t_2 - t_w)c_v$
	$=$	$2255(160 - 100)0.45$
	$=$	$60,900 \text{ Btu/h}$
Required heat for material	$=$	$2,528,700 \text{ Btu/h}$

The temperature drop $(t_2 - t_3)$ through the bed is

$$\frac{\text{Required heat}}{\text{Supplied air, (lb/h)} \times c_a} = \frac{2,528,700}{286,500 \times 0.24} = 37\degree\text{F}$$

Therefore, the exhaust air temperature is $160 - 37 = 123\degree$F.

Required heat for makeup air	$=$	$G_T(t_3 - t_1)c_a$
	$=$	$81,000(123 - 70)0.24$
	$=$	$1,030,000 \text{ Btu/h}$

The total heat required for material and makeup air is

$$2,528,700 + 1,030,000 = 3,559,000 \text{ Btu/h}$$

Additional heat that must be provided to compensate for radiation and convection losses can be calculated from the known construction of the dryer surfaces.

DRYING SYSTEM SELECTION

A general procedure for selecting a drying system is as follows:

1. Survey of suitable dryers.
2. Preliminary cost estimates of various types.
   (a) Initial investment
   (b) Operating cost
3. Drying tests conducted in prototype or laboratory units, preferably using the most promising equipment available. Sometimes a pilot plant is justified.
4. Summary of tests evaluating quality of samples of the dried products.

Factors that can overshadow the operating or investment cost include the following:

- Product quality, which should not be sacrificed
- Dusting, solvent, or other product losses
- Space limitation
- Bulk density of the product, which can affect packaging cost

Friedman (1951) and Parker (1963) discuss additional aids to dryer selection.

TYPES OF DRYING SYSTEMS

Radiant Infrared Drying

Thermal radiation may be applied by infrared lamps, gas-heated incandescent refractories, steam-heated sources, and, most often, electrically heated surfaces. Infrared heats only near the surface of a material, so it is best used to dry thin sheets.

Using infrared heating to dry webs such as uncoated materials has been relatively unsuccessful because of process control problems. Thermal efficiency can be low; heat transfer depends on the emitter's characteristics and configuration, and on the properties of the material to be dried.

Radiant heating is used for drying ink and other coatings on paper, textile fabrics, paint films, and lacquers. Inks have been specifically formulated for curing with tuned or narrow wavelength infrared radiation.

Ultraviolet Radiation Drying

Ultraviolet (UV) drying uses electromagnetic radiation. Inks and other coatings based on monomers are cure-dried when exposed to UV radiation. This method has superior properties (Chatterjee and Ramaswamy 1975): the print resists scuff, scratch, acid, alkali, and some solvents. Printing can also be done at higher speeds without damage to the web.

Major barriers to wider acceptance of UV drying include the high capital installation cost and the increased cost of inks. The cost and frequency of replacing UV lamps are greater than for infrared ovens.

Overexposure to radiation and ozone, which is formed by UV radiation's effect on atmospheric oxygen, can cause severe sunburn and possibly blood and eye damage. Safety measures include fitting the lamp housings with screens, shutters, and exhausts.

Conduction Drying

Drying rolls or drums (Figure 1), flat surfaces, open kettles, and immersion heaters are examples of direct-contact drying. The heating surface must have close contact with the material, and agitation may increase uniform heating or prevent overheating.

Conduction drying is used to manufacture and dry paper products. It (1) does not provide a high drying rate, (2) does not furnish uniform heat and mass transfer conditions, (3) usually results in a poor moisture profile across the web, (4) lacks proper control, (5) is costly to operate and install, and (6) usually creates undesirable working conditions in areas surrounding the machine. Despite these disadvantages, replacing existing systems with other forms of drying is expensive. For example, Joas and Chance (1975) report that RF (dielectric) drying of paper requires approximately four times the capital cost, six times the operating (heat) cost, and five times the maintenance cost of steam cylinder conduction drying.
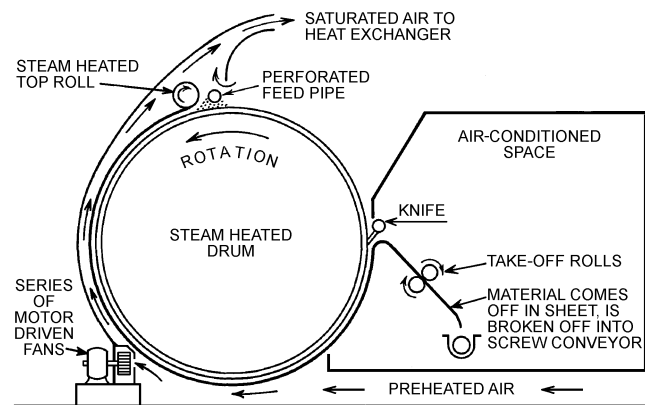
Fig. 1   Drum Dryer

However, augmenting conduction drying with dielectric drying sections offsets the high cost of RF drying and may produce savings and increased profits from greater production and higher final moisture content.

Further use of large conduction drying systems depends on reducing heat losses from the dryer, improving heat recovery, and incorporating other drying techniques to maintain quality.

Dielectric Drying

When wet material is placed in a strong, high-frequency (2 to 100 MHz) electrostatic field, heat is generated within the material. More heat is developed in the wetter areas than in the drier areas, resulting in automatic moisture profile correction. Water is evaporated without unduly heating the substrate. Therefore, in addition to its leveling properties, dielectric drying provides uniform heating throughout the web thickness.

Dielectric drying is controlled by varying field or frequency strength; varying field strength is easier and more effective. Response to this variation is quick, with neither time lag nor thermal lag in heating. The dielectric heater is a sensitive moisture meter.

Several electrode configurations are used. The platen type (Figure 2) is used for drying and baking foundry cores, heating plastic preforms, and drying glue lines in furniture. The rod or stray field types (Figure 3) are used for thin web materials such as paper and textile products. The double-rod types (over and under material) are used for thicker webs or flat stock, such as plywood.

Dielectric drying is popular in the textile industry. Because air is entrained between fibers, convection drying is slow and uneven.
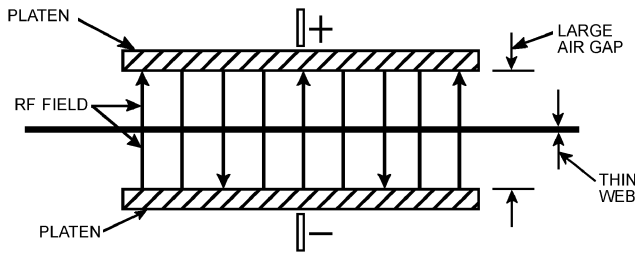
Fig. 2   Platen-Type Dielectric Dryer
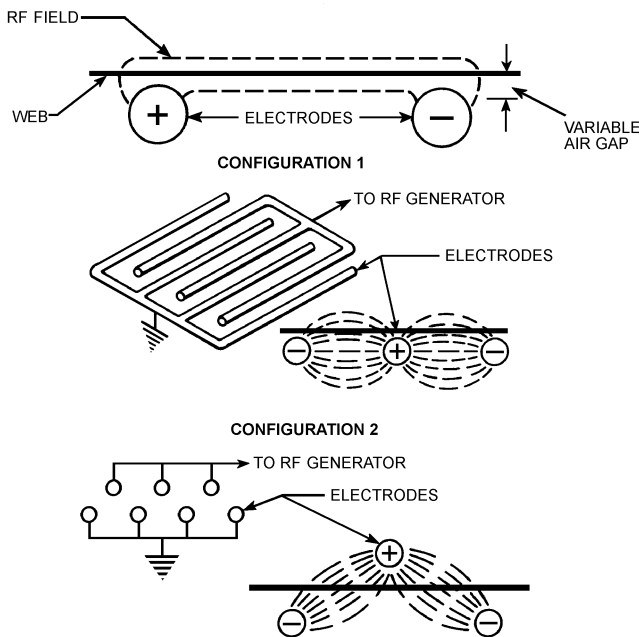
Fig. 3   Rod-Type Dielectric Dryers

Because the yarn is usually transferred to large packages immediately after drying, however, even and correct moisture content can be obtained by dielectric drying. Knitting wool seems to benefit from internal steaming in hanks.

Warping caused by nonuniform drying is a serious problem for plywood and linerboard. Dielectric drying yields warp-free products.

Dielectric drying is not cost-effective for overall paper drying but has advantages when used at the dry end of a conventional steam drum dryer. It corrects moisture profile problems in the web without overdrying. This combination of conventional and dielectric drying is synergistic: the drying effect of the combination is greater than the sum of the two types of drying. This is more pronounced in thicker web materials, accounting for as much as a 16% line speed increase and a corresponding 2% energy input increase.

Microwave Drying

Microwave drying or heating uses ultrahigh-frequency (900 to 5000 MHz) radiation. It is a form of dielectric heating and is used for heating nonconductors. Because of its high frequency, microwave equipment is capable of generating extreme power densities.

Microwave drying is applied to thin materials in strip form by passing the strip through the gap of a split waveguide. Entry and exit shielding make continuous process applications difficult. Its many safety concerns make microwave drying more expensive than dielectric drying. Control is also difficult because microwave drying lacks the self-compensating properties of dielectrics.

Convection Drying (Direct Dryers)

Some convection drying occurs in almost all dryers. True convection dryers, however, use circulated hot air or other gases as the principal heat source. Each means of mechanically circulating air or gases has its advantages.

Rotary Dryers. These cylindrical drums cascade the material being dried through the airstream (Figure 4). The dryers are heated directly or indirectly, and air circulation is parallel or counterflow. A variation is the rotating-louver dryer, which introduces air beneath the flights to provide close contact.

Cabinet and Compartment Dryers. These batch dryers range from the heated loft (with only natural convection and usually poor and nonuniform drying) to self-contained units with forced draft and properly designed baffles. Several systems may be evacuated to dry delicate or hygroscopic materials at low temperatures. Material is usually spread in trays to increase the exposed surface. Figure 5 shows a dryer that can dry water-saturated products.

When designing dryers to process products saturated with solvents, special features must be included to prevent explosive gases from forming. Safe operation requires exhausting 100% of the air circulated during the initial drying period or any part of the drying cycle when solvent is evaporating at a high rate. At the end of the purge cycle, the air is recirculated and heat is gradually applied. To prevent explosions, laboratory dryers can be used to determine the amount of air circulated, cycle lengths, and rate that heat is applied for each product. In the drying cycle, dehumidified air, which is costly, should
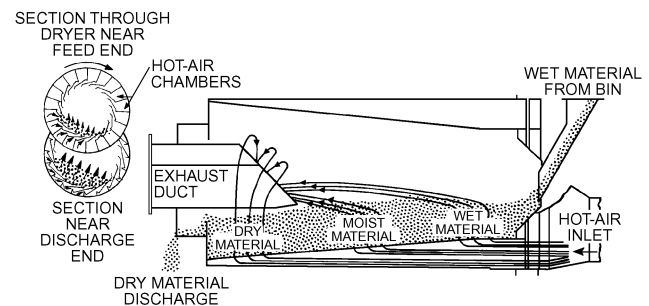
Fig. 4   Cross Section and Longitudinal Section of Rotary Dryer
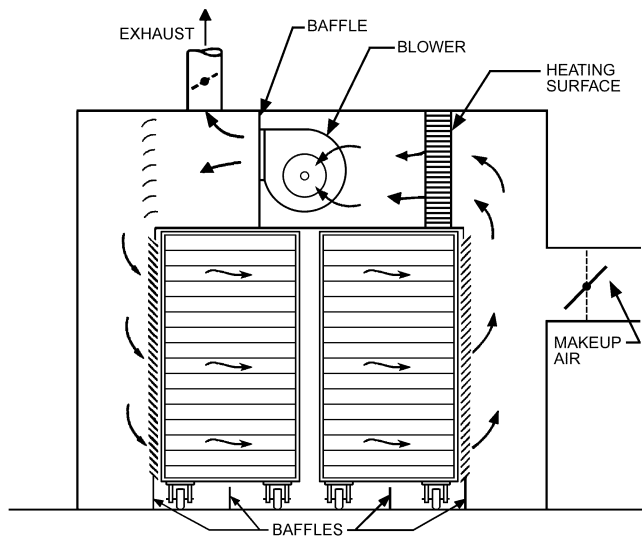
Fig. 5 Compartment Dryer Showing Trucks with Air Circulation

be recirculated as soon possible. The air *must not* be recirculated when cross-contamination of products is prohibited.

Dryers must have special safety features in case any part of the drying cycle fails. The following are some of the safety design features described in *Industrial Ovens and Driers* (FMEA 1990):

- Each compartment must have separate supply and exhaust fans and an explosion-relief panel.
- The exhaust fan blade tip speed should be 5000 fpm for forward-inclined blades, 6800 fpm for radial-tip, and 7500 fpm for backward-inclined. These speeds produce high static pressures at the fan, ensuring constant exhaust volumes under conditions such as negative pressures in the building or downdrafts in the exhaust stacks.
- Airflow failure switches in both the supply and exhaust ducts must shut off fans and the heating coil and must sound an alarm.
- A high-temperature limit controller in the supply duct must shut off the heat to the heating coil and must sound an alarm.
- An electric interlock on the dryer door must interrupt the drying cycle if the door is opened beyond a set point, such as that wide enough for a person to enter for product inspection.

Tunnel Dryers. Tunnel dryers are modified compartment dryers that operate continuously or semicontinuously. Fans circulate heated air or combustion gas is circulated by fans. The material is handled on trays or racks on trucks and moves through the dryer either intermittently or continuously. The airflow may be parallel, counterflow, or a combination obtained by center exhaust (Figure 6). Air may also flow across the tray surface, vertically through the bed, or in any combination of directions. By reheating or recirculating the air in the dryer, high saturation is reached before the air is exhausted, thus reducing the sensible heat loss.

The following problems with tunnel dryers have been experienced and should be considered in future designs:

- Operators may overload product trays to increase output, but this can overtax the system and increase drying time.
- Sometimes air from the drying tunnel is discharged into the production area, increasing the humidity. Air from the drying tunnel should be discharged to the drying system return or outside.
- Overloaded product trays add pressure drop, which decreases flow through the dryer. The control panel should indicate validated flow through the tunnel. High and low flow and high moisture levels should trigger alarms.
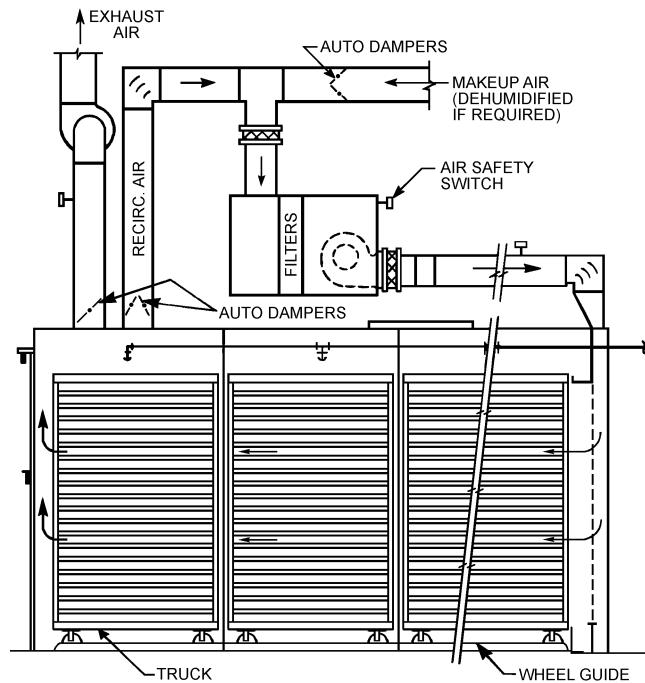
Fig. 6 Explosionproof Truck Dryer Showing Air Circulation and Safety Features
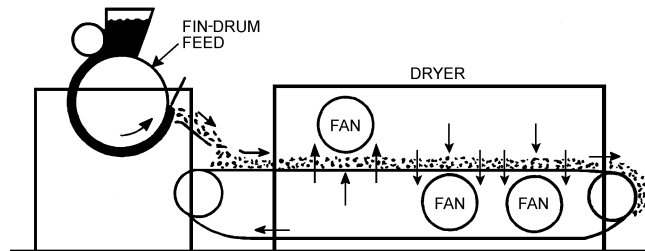
Fig. 7 Section of Blow-Through Continuous Dryer

- Cycle times can be reduced by designing dryers for cross-flow rather than end-to-end flow.

A variation of the tunnel dryer is the strictly continuous dryer, which has one or more mesh belts that carry the product through it, as shown in Figure 7. Many combinations of temperature, humidity, air direction, and velocity are possible. Hot air leaks at the entrance and exit can be minimized by baffles or inclined ends, with the material entering and leaving from the bottom.

High-Velocity Dryers. High-velocity hoods or dryers have been used to supplement conventional cylinder dryers for drying paper. When used with conventional cylinder dryers, web instability and lack of process control result. Where internal diffusion is not the controlling factor in the drying rate, applications such as thin permeable webs offer more promise.

Spray Dryers. Spray dryers have been used in producing dried milk, coffee, soaps, and detergents. Because the dried product (in the form of small beads) is uniform and drying time is short (5 to 15 s), this drying method has become more important. When a liquid or slurry is dried, the spray dryer has high production rates.

Spray drying involves atomizing a liquid feed in a hot-gas drying medium. The spray can be produced by a two-fluid nozzle, a high-pressure nozzle, or a rotating disk. Inlet gas temperatures range from 200 to 1400°F, with the high temperatures requiring special construction materials. Because thermal efficiency increases with the inlet gas temperature, high inlet temperatures are desirable. Even
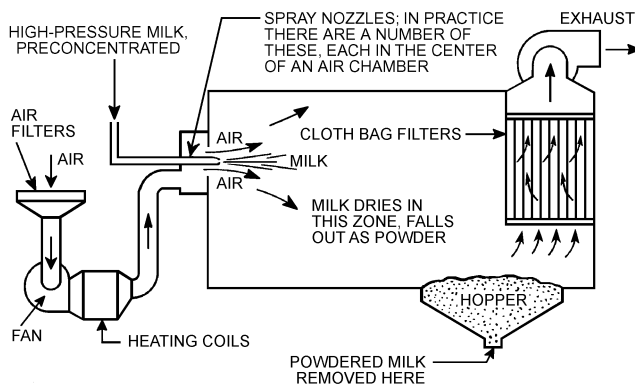
Fig. 8   Pressure-Spray Rotary Spray Dryer

heat-sensitive products can be dried at higher temperatures because of the short drying time. Hot gas flow may be either concurrent or countercurrent to the falling droplets. Dried particles settle out by gravity. Fine material in the exhaust air is collected in cyclone separators or bag filters. Figure 8 shows a typical spray drying system.

The physical properties of the dried product (such as particle size, bulk density, and dustiness) are affected by atomization characteristics and the temperature and direction of flow of the drying gas. The product's final moisture content is controlled by the humidity and temperature of the exhaust gas stream.

Currently, pilot-plant or full-scale production operating data are required for design purposes. The drying chamber design is determined by the nozzle's spray characteristics and heat and mass transfer rates. There are empirical expressions that approximate mean particle diameter, drying time, chamber volume, and inlet and outlet gas temperatures.

Freeze Drying

Freeze drying has been applied to pharmaceuticals, serums, bacterial and viral cultures, vaccines, fruit juices, vegetables, coffee and tea extracts, seafoods, meats, and milk.

The material is frozen, then placed in a high-vacuum chamber connected to a low-temperature condenser or chemical desiccant. Heat is slowly applied to the frozen material by conduction or infrared radiation, allowing the volatile constituent, usually water, to sublime and condense or be absorbed by the desiccant. Most freeze-drying operations occur between 14 and −40°F under minimal pressure. Although this process is expensive and slow, it has advantages for heat-sensitive materials (see Chapter 16 of the 2006 *ASHRAE Handbook—Refrigeration*).

Vacuum Drying

Vacuum drying takes advantage of the decrease in the boiling point of water that occurs as the pressure is lowered. Vacuum drying of paper has been partially investigated. Serious complications arise if the paper breaks, and massive sections must be removed. Vacuum drying is used successfully for pulp drying, where lower speeds and higher weights make breakage relatively infrequent.

Fluidized-Bed Drying

A fluidized-bed system contains solid particles through which a gas flows with a velocity higher than the incipient fluidizing velocity but lower than the entrainment velocity. Heat transfer between the individual particles and the drying air is efficient because there is close contact between powdery or granular material and the fluidizing gas. This contact makes it possible to dry sensitive materials without danger of large temperature differences.

The dried material is free-flowing and, unlike that from convection dryers, is not encrusted on trays or other heat-exchanging

surfaces. Automatic charging and discharging are possible, but the greatest advantage is reduced process time. Only simple controls are important: over (1) fluidizing air or gas temperatures and (2) the drying time of the material.

All fluidized-bed dryers should have explosion-relief flaps. Both the pressure and flames of an explosion are dangerous. When toxic materials are used, uncontrolled venting to the atmosphere is prohibited. Explosion suppression systems, such as pressure-actuated ammonium-phosphate extinguishers, have been used instead of relief venting. An inert dryer atmosphere is preferable to suppression systems because it prevents explosive mixtures from forming.

When organic and inflammable solvents are used in the fluidized-bed system, the closed system offers advantages other than explosion protection. A portion of the fluidizing gas is continuously run through a condenser, which strips the solvent vapors and greatly reduces air pollution problems, thus making solvent recovery convenient.

Materials dried in fluidized-bed installations include coal, limestone, cement rock, shales, foundry sand, phosphate rock, plastics, medicinal tablets, and foodstuffs. Leva (1959) and Othmer (1956) discuss the theory and methods of fluidization of solids. Clark (1967) and Vanecek et al. (1966) developed design equations and cost estimates.

Agitated-Bed Drying

Uniform drying is ensured by periodically or continually agitating a bed of preformed solids with a vibrating tray, a conveyor, or a vibrating mechanically operated rake, or, in some cases, by partial fluidization of the bed on a perforated tray or conveyor through which recycled drying air is directed. Drying and toasting cereals is an important application.

Drying in Superheated Vapor Atmospheres

When drying solids with air or another gas, the vaporized solvent (water or organic liquid) must diffuse through a stagnant gas film to reach the bulk gas stream. Because this film is the main resistance to mass transfer, the drying rate depends on the solvent vapor diffusion rate. If the gas is replaced by solvent vapor, resistance to mass transfer in the vapor phase is eliminated, and the drying rate depends only on the heat transfer rate. Drying rates in solvent vapor, such as superheated steam, are greater than those in air for equal temperatures and mass flow of the drying media.

This method also has higher thermal efficiency, easier solvent recovery, and a lower tendency to overdry, and it eliminates oxidation or other chemical reactions that occur when air is present. In drying cloth, superheated steam reduces the migration tendency of resins and dyes. Superheated vapor drying cannot be applied to heat-sensitive materials because of the high temperatures.

Commercial drying equipment with recycled solvent vapor as the drying medium is available. Installations have been built to dry textile sheeting and organic chemicals.

Flash Drying

Finely divided solid particles that are dispersed in a hot gas stream can be dried by flash drying, which is rapid and uniform. Commercial applications include drying pigments, synthetic resins, food products, hydrated compounds, gypsum, clays, and wood pulp.

Constant-Moisture Solvent Drying

In some cases it is desirable to dry organic solvents from a substance without changing moisture content. This is particularly true in drying pharmaceutical products, which are commonly bound with solvents such as isopropyl alcohol (IPA) or acetone. Loss of moisture content can affect the stability of some pharmaceutical compounds, which therefore must be liberated of bound solvents

without changing the relative humidity. Most pharmaceutical facilities producing oral solid dosage (OSD) presentations manufacture in spaces that range from 30 to 45% rh. To maintain this level of humidity at the temperatures needed to liberate the organic solvents at the required rate, an oven must be fitted with an adequately sized humidifier. Figure 9 shows the compartment dryer from Figure 5 adapted for constant-moisture drying.
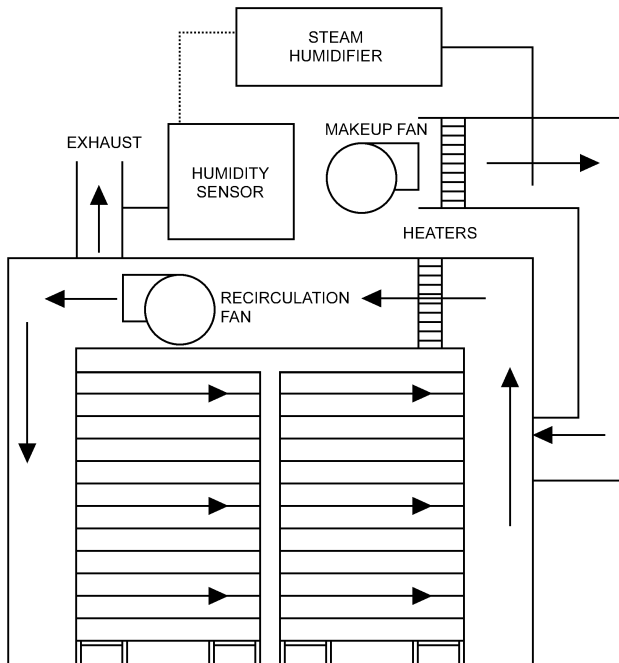
Fig. 9   Humidified Cross-Flow Tray Dryer

It is vital to size the preheat coil to the humidifier to allow enough "room" to provide the humidification level required. The amount of preheat is usually enough to provide makeup air to the oven at 90% rh. This allows the oven heaters to control drying temperature at the more common oven humidity levels of 30 to 45% rh. If electric heat is used, the ability to constantly vary the capacity of the heaters must be provided; silicon-controlled rectifiers (SCRs) are commonly used.

Additional insulation on the outside of the oven and the ductwork from the humidifier section onward should also be considered. Care must be taken to ensure that unwanted condensation does not form inside the oven. Dripping moisture can sometimes ruin the product, causing a substantial economic loss. If the product is pharmaceutical, then the humidifier makeup water source should be deionized or produced to comply with U.S. Pharmacopoeia XXIII, Supplement 8 (effective May 1998).

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CHAPTER 29

VENTILATION OF THE INDUSTRIAL ENVIRONMENT

INDUSTRIAL environments require ventilation to reduce exposure to excess heat and contaminants that are generated in the workplace; in some situations, cooling may also be required. Ventilation is primarily used to control excess heat, odors, and hazardous particulate and chemical contaminants that could affect the health and safety of industrial workers or, in some cases, be ignited or become combustible when allowed to accumulate beyond their lower flammable limit (LFL). Excess heat and contaminants can best be controlled by using local exhaust systems whenever possible. Local exhaust systems exhaust heated air and contaminants at the source of the heat and contaminants and may require lower airflows than general (dilution) ventilation. For more information, see Chapter 30.

General ventilation can be provided by mechanical (fan) systems, by natural draft, or by a combination of the two. Combination systems could include mechanically driven (fan-driven) supply air with air pressure relief through louvers or other types of vents, and mechanical exhaust with air replacement inlet louvers and/or doors.

Mechanical (fan-driven) supply systems provide the best control and the most comfortable and uniform environment, especially when there are extremes in local climatic conditions. The systems typically consist of an inlet section, a filter, heating and/or cooling equipment, fans, ductwork, and air diffusers for distributing air within the workplace. When toxic gases or vapors are not present, air cleaned in the general exhaust system or in free-hanging filter units can be recirculated via a return duct. Air recirculation may reduce heating and cooling costs.

A general exhaust system, which removes air contaminated by gases, vapors, or particulates not captured by local exhausts, usually consists of one or more fans, plus inlets, ductwork, and an air cleaner or filters. After air passes through the filters, it is either discharged outside or partially recirculated to the building workplace. The air filter system's cleaning efficiency should conform to environmental regulations and depends on factors such as building location, background contaminant concentrations in the atmosphere, type of contaminants, and height and velocity of the building exhaust discharge.

Many industrial ventilation systems must handle simultaneous exposures to heat and hazardous substances. In these cases, the required ventilation can be provided by a combination of local exhaust, general ventilation air supply, and general exhaust systems. The ventilation engineer must carefully analyze supply and exhaust air requirements to determine the worst case. For example, air supply makeup for hood exhaust may be insufficient to control heat exposure. It is also important to consider seasonal climatic effects on ventilation system performance, especially for natural ventilation systems.

In specifying acceptable chemical contaminant and heat exposure levels, the industrial hygienist or industrial hygiene engineer must consult the appropriate governing standards and guidelines. The standard levels for most chemical and heat exposures are time-weighted averages that allow excursions above the limit as long as they are balanced by equivalent excursions below the limit during the workday. However, exposure level standards for heat and contaminants are not lines of demarcation between safe and unsafe exposures. Rather, they represent conditions to which it is believed nearly all workers may be exposed day after day without adverse effects (ACGIH 2006a). Because a small percentage of workers may be overly stressed at exposure levels below the standards, it is prudent to design for exposure levels below the limits.

In the case of exposure to toxic chemicals, the number of contaminant sources, their generation rates, and the effectiveness of exhaust hoods may not be known. Consequently, the ventilation engineer must rely on common ventilation industrial hygiene practice when designing toxic chemical controls. Close cooperation among the industrial hygienist, process engineer, and ventilation engineer is required.

In the case of exposure to flammable or ignitable chemicals, the specific gravity of the contaminant source(s), their concentration, and the rating of all electrical devices within the space, along with any source or point of excessive heat, must be carefully considered to prevent possible loss of life or severe injury. As with toxic chemicals, cooperation of knowledgeable experts, including electrical engineers, is required.

This chapter describes principles of ventilation practice and includes other information on hygiene in the industrial environment. Publications from the British Occupational Hygiene Society (1987), National Safety Council (2002), U.S. National Institute for Occupational Safety and Health (NIOSH 2005), and the U.S. Department of Health and Human Services (1986) provide further information on industrial hygiene principles and their application.

VENTILATION DESIGN PRINCIPLES

General Ventilation

General ventilation supplies and/or exhausts air to provide heat relief, dilute contaminants to an acceptable level, and replace exhaust air. Ventilation can be provided by natural or mechanical supply and/or exhaust systems. Industrial areas must comply with ANSI/ASHRAE *Standard* 62.1-2004 and other standards as required [e.g., by the National Fire Protection Association (NFPA)]. Outdoor air is unacceptable for ventilation if it is known to contain any contaminant at a concentration above that given in ANSI/ASHRAE *Standard* 62.1. If air is thought to contain any contaminant not listed in the standard, guidance on acceptable exposure levels should be obtained from OSHA standards (ACGIH 2006a). General ventilation rates must be high enough to dilute the carbon dioxide produced by occupants.

For complex industrial ventilation problems, experimental scale models and computational fluid dynamics (CFD) models are often used in addition to field testing.

Makeup Air

For safe, effective operation, most industrial plants require makeup air to replace the large volumes of air exhausted to provide acceptable comfort and safety for personnel and acceptable conditions for process operations. Makeup air, consistently provided by good air distribution, allows more effective cooling in the summer and more efficient and effective heating in the winter. Installing windows or other inlets that cannot function in stormy weather is discouraged. Some factors to consider in makeup air design include the following:

- Makeup air must be sufficient to replace air being exhausted or consumed by combustion processes, local and general exhaust systems (see Chapter 30), or process equipment. (Large air compressors can consume a large amount of air and should be considered if air is drawn from within the building.)
- Makeup air systems should be designed to eliminate uncomfortable crossdrafts by properly arranging supply air outlets, and to prevent infiltration (through doors, windows, and similar openings) that may make hoods unsafe or ineffective, defeat environmental control, bring in or stir up dust, or adversely affect processes by cooling or disturbances. The design engineer needs to consider side drafts, and other sources of air movement close to the capture area of a local exhaust hood. Caplan and Knutson (1977, 1978) found that air movement in front of laboratory hoods can cause contaminants to escape from the hood and into the operator's breathing zone. In industrial applications, it is common to see large fans blowing air on workers in front of the hood. This can render the local exhaust hood ineffective to the point that no protection is provided for the worker.
- Makeup air should be obtained from the cleanest source. Supply air can be filtered, but infiltration air cannot. For transfer air use, see ANSI/ASHRAE *Standard* 62.1.
- Makeup air for spaces contaminated by toxic, ignitable, or combustible chemicals may have to be acquired through carefully sealed ductwork from an area know to be free of any contamination and be supplied at sufficient rates and pressures to (1) remove all contamination, and (2) prevent infiltration of similar contaminants from surrounding areas or adjacent spaces.
- Makeup air should be used to control building pressure and airflow from space to space to (1) avoid positive or negative pressures that make it difficult or unsafe to open doors, (2) minimize drafts, and (3) prevent infiltration.
- Makeup air should be used to confine contaminants and reduce their concentration and to control temperature, humidity, and air movement.
- Makeup air systems should be designed to recover heat and conserve energy (see the section on Energy Conservation and Recovery).

ACGIH (2006b) provides information on adverse conditions that may result from specific negative pressure levels in buildings.

GENERAL COMFORT AND DILUTION VENTILATION

Effective air diffusion in ventilated rooms and the proper quantity of conditioned air are essential for creating an acceptable working environment, removing contaminants, and reducing initial and operating costs of a ventilation system. Ventilation systems must supply air at the proper velocity and temperature, with contaminant concentrations within permissible limits. In most cases, the objective is to provide tolerable (acceptable) working conditions rather than comfort (optimal) conditions.

General ventilation system design is based on the assumption that local exhaust ventilation, radiation shielding, and equipment insulation and encapsulation have been selected to minimize both heat load and contamination in the workplace (see the section on Heat Control in Industrial Work Areas). In cold climates, infiltration and heat loss through the building envelope may need to be minimized by pressurizing buildings.

For more information on dilution ventilation, see ACGIH (2006b).

Quantity of Supplied Air

Sufficient air must be supplied to replace air exhausted by process ventilation and local exhausts, to dilute contaminants (gases, vapors, or airborne particles) not captured by local exhausts, and to provide the required thermal environment. The amount of supplied air should be the largest of the amounts needed for temperature control, dilution, and replacement.

Air Supply Methods

Air supply to industrial spaces can be by natural or mechanical ventilation systems. Although natural ventilation systems driven by gravity forces and/or wind effect are still widely used in industrial spaces (especially in hot premises in cold and moderate climates), they are inefficient in large buildings, may cause drafts, and may not solve air pollution problems because there is no practical filtration method available. Thus, most ventilation systems in industrial spaces are either mechanical (fan-driven) or a combination of mechanical supply with natural exhaust, using louvers or doors for air pressure relief (or for air replacement in exhaust systems).

The most common methods of air supply to industrial spaces are mixing, displacement, and localized.

Mixing Air Distribution. In mixing systems, air is normally supplied at velocities much greater than those acceptable in the occupied zone. Supply air temperature can be above, below, or equal to the air temperature in the occupied zone, depending on the heating/cooling load. The supply air diffuser jet mixes with room air by entrainment, which reduces air velocities and equalizes the air temperature. The occupied zone is ventilated either directly by the air jet or by reverse flow created by the jet. Properly selected and designed mixing air distribution creates relatively uniform air velocity, temperature, humidity, and air quality conditions in the occupied zone and over the room height.

Displacement Ventilation Systems. Conditioned air slightly cooler than the desired room air temperature in the occupied zone is supplied from air outlets at low air velocities (~100 fpm or less). Because of buoyancy, the cooler air spreads along the floor and floods the room's lower zone. Air close to the heat source is heated and rises upward as a convective air stream; in the upper zone, this stream spreads along the ceiling. The height of the lower zone depends on the air volume and temperature supplied to the occupied zone and on the amount of convective heat discharged by the sources.

Typically, outlets are located at or near the floor, and supply air is introduced directly into the occupied zone. In some applications (e.g., in computer rooms or hot industrial buildings), air may be supplied to the occupied zone through a false floor. Exhaust or air returns are located at or close to the ceiling or roof.

Displacement ventilation is common in Scandinavia and is becoming popular in other European countries. It is an option when contaminants are released in combination with surplus heat, and contaminated air is warmer (more buoyant) than the surrounding air. Further information on displacement air distribution systems can be found in Goodfellow and Tahti (2001).

Localized Ventilation. Air is supplied locally for occupied regions or a few permanent work areas (Figure 1). Conditioned air is supplied toward the breathing zone of the occupants to create comfortable conditions and/or to reduce the concentration of pollutants. These zones may have air 5 to 10 times cleaner than the surrounding air. In localized ventilation systems, air is supplied through one of the following devices:

A. AIR SHOWERS

B. AIR OASIS WITH HORIZONTAL AIR SUPPLY

C. AIR OASIS WITH VERTICAL AIR SUPPLY
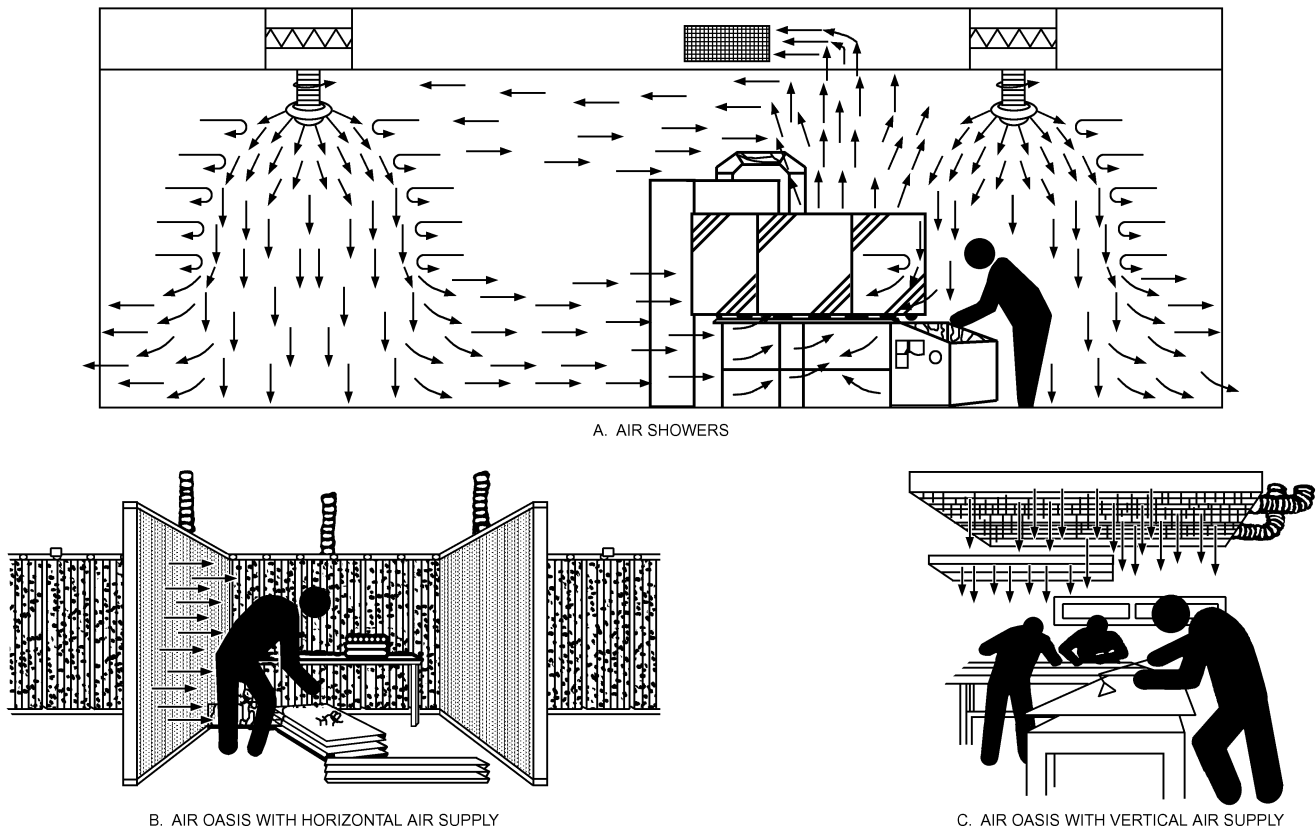
Fig. 1 Localized Ventilation Systems

- Nozzles or grilles (e.g., for spot cooling), specially designed low-velocity/low-turbulence devices
- Perforated panels suspended on vertical duct drops and positioned close to the workstation

Local Area and Spot Cooling

In hot workplaces that have only few work areas, it is likely impractical and energy-inefficient to maintain a comfortable environment in the entire space. However, air-conditioned cabins, individual cooling, and spot cooling can improve working conditions in occupied areas.

Air-conditioned cabins can provide thermal comfort. Control rooms for monitoring production and manufacturing processes can use this technology.

Spot cooling, probably the most popular method of improving the thermal environment, can be provided by radiation (changing mean radiant temperature), by convection (changing air velocity and/or air supply temperatures), or both. Spot-cooling equipment is fixed at the workstation, whereas in **individual cooling**, the worker wears the equipment.

Locker Room, Toilet, and Shower Space Ventilation

Ventilation of locker rooms, toilets, and shower spaces is important in industrial facilities to remove odor and reduce humidity. In some industries, adequate control of workroom contamination requires prevention of both ingestion and inhalation, so adequate hygienic facilities, including appropriate ventilation, may be required in locker rooms, changing rooms, showers, lunchrooms, and break rooms. State and local regulations should be consulted early in design.

Supply air may be introduced through doors or wall grilles. In some cases, plant air may be so contaminated that filtration or (preferably) mechanical ventilation may be required. When control of

workroom contaminants is inadequate or not feasible, minimizing the level of contamination in the locker rooms, lunchrooms, and break rooms by pressurizing these areas with excess supply air can reduce employee exposure.

When mechanical ventilation is used, the supply system should have adequate ducting and air distribution devices, such as diffusers or grilles, to distribute air throughout the area.

In locker rooms, exhaust should be taken primarily from the toilet and shower spaces as needed, and the remainder from the lockers and the room ceiling. ASHRAE *Standard* 62.1 provides requirements in this area.

Roof Ventilators

Roof ventilators are heat escape ports located high in a building and should be properly enclosed for weathertightness (Goodfellow 1985). Stack effect and some wind induction are the motive forces for gravity- (buoyancy-) driven operation of continuous and round ventilators. Round ventilators can be equipped with a fan barrel and motor, allowing gravity or forced ventilation operation.

Many ventilator designs are available, including the **low ventilator**, which consists of a stack fan with a rain hood, and a **ventilator with a split butterfly closure** that floats open to discharge air and closes by a counterweight. Both use minimum enclosures and have little or no gravity capacity. Split butterfly dampers tend to increase fan airflow noise and are subject to damage from slamming during strong wind conditions. Because noise is frequently a problem in powered roof ventilators, the manufacturer's sound rating should be reviewed. Sound attenuators should be installed where required to meet the design sound ratings.

Continuous ventilation monitors remove substantial, concentrated heat loads most effectively. One type, the **streamlined continuous ventilator**, is efficient, weathertight, and designed to prevent backdraft; it usually has dampers that may be closed in

winter to conserve building heat. Its capacity is limited only by the available roof area and the proper location and sizing of low-level air inlets. Continuous ventilation to achieve a slight pressure above the surrounding atmosphere (referred to as **pressurization** by the National Fire Protection Association) can also be used to reduce or declassify the electrical classification of enclosed spaces. Typically, reductions from Class I, Zone 1 or Division 1 to Class I, Zone 2 or Division 2 can be achieved by following the recommendations of NFPA *Standard* 496. This allows using general-purpose electrical devices instead of Zone 2 or Division 2 devices or using Zone 2 or Division 2 electrical devices instead of Zone 1 or Division 1 devices, which (1) greatly reduces the cost of electrical equipment and (2) provides a sound alternative when particular devices are not available for the higher (more volatile) electrical area classifications.

Gravity ventilators, also highly effective, have low operating costs, do not generate noise, and are self-regulating (i.e., higher heat release increases airflow through the ventilators). Care must be taken to ensure positive pressure at the ventilators, particularly during the heating season. Otherwise, outside air will enter the ventilators.

Next according to their heat removal capacity are (1) round gravity or windband ventilators, (2) round gravity ventilators with fan and motor added, (3) low-hood powered ventilators, and (4) vertical upblast powered ventilators. The shroud for the vertical upblast design has a peripheral baffle to deflect air upward instead of downward. Vertical discharge is highly desirable to reduce roof damage caused by hot air if it contains condensable oil or solvent vapor. Ventilators with direct-connected motors are desirable to avoid belt maintenance on units in difficult locations. Round gravity ventilators are applicable for warehouses with light heat loads and for manufacturing areas with high roofs and light loads.

Streamlined continuous ventilators must operate effectively without mechanical power. To ensure ventilator performance, sufficient low-level openings must be provided for incoming air; insufficient inlet area and significant space air currents are the most common reasons gravity roof ventilators malfunction. A positive supply of air around hot equipment may be necessary in large buildings where external wall inlets are remote from the equipment. Chapter 27 of the 2005 *ASHRAE Handbook—Fundamentals* has additional information on ventilation and infiltration.

The cost of electrical power for mechanical ventilation over that of roof ventilators can be offset by the advantage of constant airflow. Mechanical ventilation can also create the pressure differential necessary for good airflow, even with small inlets. Inlets should be sized correctly to avoid infiltration and other problems caused by high negative pressure in the building. Often, a mechanical system is justified to supply enough makeup air to maintain the work area under positive pressure.

Roof ventilators can comprise either mechanically operated openings or fan-powered mechanical exhaust. Operator-assisted openings or dampers are usually used in shops with high ceilings, and must be installed when natural ventilation is used to provide air to the space.

HEAT CONTROL

Ventilation control alone may frequently be inadequate for meeting heat stress standards for industrial work areas. Optimum solutions may involve additional controls such as spot cooling, changes in work/rest patterns, and radiation shielding.

Ventilation for Heat Relief

Many industrial processes release large amounts of heat and moisture to the environment. In such environments, it may not be economically feasible to maintain comfort conditions (ASHRAE *Standard* 55), particularly during summer. Comfortable conditions are not physiologically necessary: the body must be in thermal balance with the environment, but this can occur at temperature and humidity conditions well above the comfort zone. In areas where heat and moisture generated by a process are low to moderate, comfort conditions may not have to be provided if personnel exposures are infrequent and brief. In such cases, ventilation may be the only control necessary to prevent excessive physiological heat stress.

The engineer must distinguish between control needs for hot/dry industrial areas and warm/moist conditions. In hot/dry areas, a process gives off only sensible (primarily convective and radiant) heat without adding moisture to the air. This increases the heat load on exposed workers, but the rate of cooling by evaporation of perspiration may not be significantly reduced. Body heat equilibrium may be maintained, but could cause excessive perspiration. Hot/dry work situations occur around furnaces, forges, metal-extruding and rolling mills, glass-forming machines, etc.

In warm/moist conditions, a wet process may generate a significant latent heat load. The rise in sensible heat load on workers may be insignificant, but the increased moisture content of the air can seriously reduce cooling by evaporation of perspiration, making warm/moist conditions potentially more hazardous than hot/dry. Typical warm/moist operations are found in textile mills, laundries, dye houses, and deep mines, where water is used extensively for dust control.

Industrial heat load is also affected by local climate. Solar heat gain and elevated outdoor temperatures increase the heat load at the workplace, but may be insignificant compared to process heat generated locally. The moisture content of outdoor air is an important factor that can affect hot/dry work situations by restricting an individual's evaporative cooling. For warm/moist conditions, solar heat gain and elevated outdoor temperatures are more important because moisture contributed by outdoor air is insignificant compared to that released by the process.

Both ASHRAE *Standard* 55 and International Organization for Standardization (ISO) *Standard* 7730 specify thermal comfort conditions for humans.

Methods for evaluating the general thermal state of the body both in comfort conditions and under heat and cold stress are based on analysis of the heat balance for the human body, as discussed in Chapter 8 of the 2005 *ASHRAE Handbook—Fundamentals*. A person may find the thermal environment unacceptable or intolerable because of local effects on the body caused by asymmetric radiation, air velocity, vertical air temperature differences, or contact with hot or cold surfaces (floors, machinery, tools, etc.).

Heat Stress—Thermal Standards

Another heat stress indicator for evaluating an environment's heat stress potential is the **wet-bulb globe temperature** (WBGT), defined as follows:

Outdoors with solar load

$$WBGT = 0.7t_{nwb} + 0.2t_g + 0.1t_{db} \tag{1}$$

Indoors, or outdoors with no solar load

$$WBGT = 0.7t_{nwb} + 0.3t_g \tag{2}$$

where

t_{nwb} = naturally ventilated wet-bulb temperature (no defined range of air velocity; different from saturation temperature or psychrometric wet bulb temperature), °F
t_g = globe temperature (Vernon bulb thermometer, 6 in. diameter), °F
t_{db} = dry-bulb temperature (sensor shaded from solar radiation), °F

Coefficients in Equations (1) and (2) represent the fractional contributions of the component temperatures.

Exposure limits for heat stress for different levels of physical activity are shown in Figure 2 (NIOSH 2005), which depicts the allowable work regime (in terms of rest periods and work periods each hour) for different levels of work over a range of WBGT. When applying Figure 2, assume that the rest area has the same WBGT as

the work area. The curves are valid for workers acclimatized to heat. ASHRAE *Standard* 62.1-2004 provides some metabolic rates for different activities that can be used with Figure 2. Refer to NIOSH (2005) for recommended WBGT limits for nonacclimatized workers.

The **WBGT index** is an international standard (ISO *Standards* 7243 and 7730) for evaluating hot environments. The WBGT index and activity levels should be evaluated on 1 h mean values; that is, WBGT and activity are measured and estimated as time-weighted averages on a 1 h basis for continuous work, or on a 2 h basis when exposure is intermittent. Although recommended by NIOSH, the WBGT has not been accepted as a legal standard by the Occupational Safety and Health Administration (OSHA). It is generally used in conjunction with other methods to determine heat stress.

Although Figure 2 is useful for evaluating heat stress exposure limits, it is of limited use for control purposes or for evaluation of comfort. Air velocity and psychrometric wet-bulb measurements are usually needed to specify proper controls, and are only measured indirectly in WBGT determinations. Information on other useful tools, including the heat stress index (HSI), can be found in Chapter 8 of the 2005 *ASHRAE Handbook—Fundamentals* and in ISO *Standards* 7243, 7730, and 7933.

The thermal relationship between humans and their environment is determined by four independent variables:

- Air temperature
- Radiant temperatures
- Moisture content of the air
- Air velocity

Together with the rate of internal heat production (metabolic rate), these factors may combine in various ways to create different degrees of heat stress. The HSI is defined as the percent of the skin that is wetted by perspiration:

Fig. 2   Recommended Heat Stress Exposure Limits for Heat-Acclimatized Workers
[Adapted from NIOSH (1986)]

$$HSI = E_{sk}/E_{max} \times 100 \qquad (3)$$

where

E_{sk} = evaporative heat loss from the skin, Btu/h·ft^2
E_{max} = maximum possible evaporative heat loss from the skin, Btu/h·ft^2

and incorporates relative contributions of metabolism, radiant heat gain (or loss), convective heat gain (or loss), and evaporative (perspiration) heat gain (or loss). For supplemental information on evaluation and control of heat stress using methods such as reduction of radiation, changes in work/rest pattern, spot cooling, and cooling vests and suits, refer to ACGIH (2006b), Brief et al. (1983), Caplan (1980), and NIOSH (2005).

Heat Exposure Control

Control at Source. Heat exposure can be reduced by insulating hot equipment or locating it in zones with good general ventilation or outdoors, covering steaming water tanks, providing covered drains for direct removal of hot water, and maintaining tight joints and valves where steam may escape.

Local Exhaust Ventilation. Local exhaust ventilation removes heated air generated by a hot process and/or nonbuoyant gases emitted by process equipment, while removing a minimum of air from the surrounding space. Local exhaust systems are discussed in detail in Chapter 30.

Radiation Shielding. In some industries, the major environmental heat load is radiant heat from hot objects and surfaces, such as furnaces, ovens, furnace flues and stacks, boilers, molten metal, hot ingots, castings, and forgings. Because air temperature has no significant effect on radiant heat flow, ventilation is of little help in controlling such exposure. The only effective control is to reduce the amount of radiant heat impinging on the workers. Radiant heat exposure can be reduced by insulating or placing radiation shields around the source.

Radiation shields are effective in the following forms:

- **Reflective shielding**. Sheets of reflective material or insulating board are temporarily attached to the hot equipment or arranged in a semiportable floor stand.
- **Absorptive shielding (water-cooled)**. These shields absorb and remove heat from hot equipment.
- **Transparent shields**. Heat-reflective tempered plate glass, reflective metal chain curtains, and close-mesh wire screens moderate radiation without obstructing the view of hot equipment.
- **Flexible shielding**. Aluminum-treated fabrics give a high degree of radiation shielding.
- **Protective clothing**. Reflective garments such as aprons, gauntlet gloves, and face shields provide moderate radiation shielding. For extreme radiation exposures, complete suits with vortex tube cooling may be required.

If the shield is a good reflector, it remains relatively cool in severe radiant heat. Bright or highly polished tinplate, stainless steel, and ordinary flat or corrugated aluminum sheets are efficient and durable. Foil-faced plasterboard, although less durable, reflects well on one side. To be efficient, however, the reflective shield must remain bright. Radiation shields are much more efficient when used in multiple layers; they should reflect the radiant heat back to the primary source, where it can be removed by local exhaust. However, unless the shield completely surrounds the primary source, some infrared energy is reflected into the cooler surroundings and possibly into an occupied area. The direction of the reflected heat should be studied to ensure proper shielding installation.

Spot Cooling. If the workplace is located near a source of radiant heat that cannot be entirely controlled by radiation shielding, spot cooling can be used. See Chapter 33 in the 2005 *ASHRAE Handbook—Fundamentals* and data from spot-cooling diffuser manufacturers for further information.
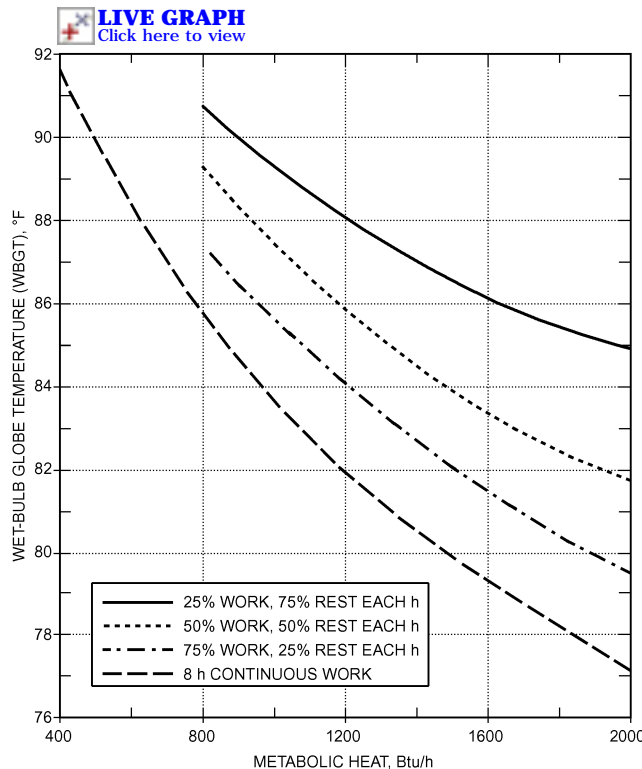
ENERGY CONSERVATION AND RECOVERY

Because of the large air volumes required to ventilate industrial plants, energy conservation and recovery should be practiced, and provides substantial savings. Energy recovery should be incorporated into preliminary planning for an industrial plant. When selecting energy recovery equipment, ensure that materials are compatible with all fumes that may be exhausted. Verify the acceptability of energy recovery with local codes.

In some cases, it is possible to provide unheated or partially heated makeup air to the building. Although most energy conservation and recovery methods in this section apply to heating, the savings possible with cooling systems are similar. The following are some methods of energy conservation and recovery:

- In the original design phase, process and equipment insulation and heat shields should be provided to minimize heat loads. Vaporproofing and reducing the glass area may be required. Exhaust requirements for hoods and processes should be reviewed and kept to a practical, safe minimum; for more on local exhaust systems, see Chapter 30.
- Design the supply and exhaust general ventilation systems for optimal operation throughout the year. Air should be supplied as close to the occupied zone as possible. Recirculated air should be used in winter makeup, and unheated or partially heated air should be brought to hoods and processes (ACGIH 2006b).
- Supply air can be passed through air-to-air, liquid-to-air, or hot-gas-to-air heat exchangers to recover building or process heat. Rotary, regenerative, coil energy recovery (runaround), and air-to-air heat exchangers are discussed extensively in Chapter 44 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*. Energy recovery is also discussed in Chapter 7 of ACGIH (2006b).
- Operate the system for economy. Shut systems down at night or on weekends whenever possible, and operate makeup air in balance with the needs of process equipment and hoods. Keep heating supply air temperatures at the minimum, and cooling supply temperatures at the maximum, consistent with process needs and employee comfort. Keep the building in pressure balance so that uncomfortable drafts do not necessitate excessive heating.
- Contaminant concentrations in any recirculated air must be determined so that allowable limits in the space are not exceeded. As recirculated air returns to the space, the concentration of contaminants in the partially filtered return air adds to the contaminant levels already existing in the space. It must be determined whether the concentration increases beyond the allowable time-weighted average (TWA) during the period for which the worker is exposed. This period is usually assumed to be 8 h for an 8 h work shift, but could be any period of exposure.

The TWA at the workers breathing zone is (ACGIH 2006b)

$$C_B = \frac{Q_B}{Q_A}(C_G - C_M)(1 - f) + (C_O - C_M)f \\ + K_B C_R + (1 - K_B)C_M \qquad (4)$$

where

C_B = TWA worker breathing zone contaminant concentration with recirculation, ppm
Q_B = total ventilation airflow without recirculation, cfm
Q_A = total ventilation airflow with recirculation, cfm
C_G = average space concentration without recirculation, ppm
f = fraction of time worker spends at workstation
C_O = TWA contaminant concentration at breathing zone of workstation without recirculation, ppm
K_B = fraction of worker breathing zone that consists of recirculated air, 0 to 1.0
C_R = recirculated air (after air cleaner) discharge concentration, ppm, or

$$C_R = \frac{(1 - \eta)(C_E - K_R C_M)}{1 - (1 - \eta)K_R} \qquad (5)$$

η = fractional air cleaner efficiency for contaminant
C_E = (local) exhaust concentration without recirculation, ppm
K_R = fraction of exhaust that that is recirculated air, 0 to 1.0
C_M = replacement air contaminant concentration, ppm

Other recirculation systems are given in Chapter 8 of Goodfellow and Tahti (2001).

Example 1. An industrial space uses 10,000 cfm for ventilation, of which 5000 cfm is general exhaust and 5000 cfm local exhaust (ACGIH 2006b). Local exhaust is recirculated through an air cleaner with an efficiency of 0.8. Recirculated air is directed toward the worker spaces, such that $K_B = 0.5$ and $K_R = 0.8$ (more of the recirculated air is locally exhausted than enters the worker's breathing zone). The worker is at the workstation 100% of the time ($f = 1$). The makeup air has a concentration of 5 ppm (C_M), the local exhaust has a concentration of 500 ppm (C_E), the space has an average concentration of 20 ppm (C_G), and without recirculation the worker's breathing zone is 35 ppm (C_O).

Solution: The concentration C_B at the breathing zone with recirculation is determined from

$$C_R = \frac{(1 - 0.75)[500 - 0.8(5)]}{1 - (1 - 0.75)(0.8)} = 155 \text{ ppm}$$

and

$$C_B = \frac{10,000}{5000}(20 - 5)(1 - 1) + (35 - 5)(1) + 0.5(155) \\ + (1 - 0.5)5 = 110 \text{ ppm}$$

which may or may not exceed the TWA or threshold limit value (TLV) of the worker space, depending on the specific contaminant.

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CHAPTER 30

INDUSTRIAL LOCAL EXHAUST SYSTEMS

INDUSTRIAL exhaust ventilation systems collect and remove airborne contaminants consisting of particulate matter (dust, fumes, smokes, fibers), vapors, and gases that can create a hazardous, unhealthy, or undesirable atmosphere. Exhaust systems can also salvage usable material, improve plant housekeeping, and capture and remove excessive heat or moisture. Often, industrial ventilation exhaust systems are considered life-safety systems and can contain hazardous gases and/or particles.

Industrial exhaust systems also have to comply with ANSI/ASHRAE *Standard* 62.1-2004 and other standards as required [e.g., by the National Fire Protection Agency (NFPA)].

Local Exhaust Versus General Ventilation

Local exhaust ventilation systems can be the most cost-effective method of controlling air pollutants and excessive heat. For many manual operations, capturing pollutants at or near their source is the only way to ensure compliance with threshold limit values (TLVs) in the worker's breathing zone. Local exhaust ventilation optimizes ventilation exhaust airflow, thus optimizing system operating costs.

In some industrial ventilation designs, the emphasis is on filtering air captured by local exhausts before exhausting it to the outdoors or returning it to the production space. As a result, these systems are evaluated by filter efficiency or total particulate removal. However, if only a small percentage of emissions are captured, the degree of separation efficiency sometimes becomes irrelevant.

For a process exhaust system in the United States, the design engineer must verify if the system is permitted by the 1990 Clean Air Act. For more information, see the Environmental Protection Agency's Web site (www.epa.gov).

The pollutant-capturing efficiency of local ventilation systems depends on hood design, the hood's position relative to the source of contamination, temperature of the source being exhausted, and exhaust airflow. Selection and position of the hood significantly influence initial and operating costs of both local and general ventilation systems. In addition, poorly designed and maintained local ventilation systems can cause deterioration of building structures and equipment, negative health effects, and decreased worker productivity.

No local exhaust ventilation system is 100% effective in capturing pollutants and/or excess heat. In addition, installation of local exhaust ventilation system may not be possible in some circumstances, because of the size or mobility of the process. In these situations, general ventilation is needed to dilute pollutants and/or excess heat (where pollutants are toxic or present a health risk to workers, dilution ventilation should be avoided). Air supplied by the general ventilation system is usually heated and can be conditioned. Supply air replaces air extracted by local and general exhaust systems and improves comfort conditions in the occupied zone.

Chapter 12 of the 2005 *ASHRAE Handbook—Fundamental* covers definitions, particle sizes, allowable concentrations, and upper and lower explosive limits of various air contaminants. Chapter 29 of this volume, Goodfellow and Tahti (2001), and Chapter 2 of *Industrial Ventilation: A Manual of Recommended Practice* (American Conference of Governmental Industrial Hygienists [ACGIH] 2004) detail steps to determine air volumes necessary to dilute contaminant concentration using general ventilations.

Sufficient makeup air must be provided to replace air removed by the exhaust system. If replacement air is insufficient, building pressure becomes negative relative to atmospheric pressure. Negative building pressure allows air to infiltrate through open doors, window cracks, and backfeed through combustion equipment vents. As little negative pressure as 0.05 in. of water can cause drafts and might cause backdrafts in combustion vents, thereby creating a potential health hazard. Negative plant pressure can also cause excessive energy use. If workers near the plant perimeter complain about cold drafts, unit heaters are often installed. Heat from these units often is drawn into the plant interior, overheating the interior. Too often, this overheating is addressed by exhausting more air from the interior, causing increased negative pressure and more infiltration. Negative plant pressure reduces the exhaust volumetric flow rate because of increased system resistance, which can also decrease local exhaust efficiencies. Wind effects on building balance are discussed in Chapter 16 of the 2005 *ASHRAE Handbook—Fundamentals*.

Positive-pressure plants and balanced plants (those with equal exhaust and replacement air rates) use less energy. However, if there are clean and contaminated zones in the same building, excessive supply airflow in contaminated zones can cause contaminants to move from the contaminated zone into clean(er) zones, which is undesirable.

Exhaust system discharge may be regulated under various federal, state, and local air pollution control regulations or ordinances. These regulations may require exhaust air treatment before discharge to the atmosphere. Chapter 25 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment* provides guidance and recommendations for discharge air treatment.

LOCAL EXHAUST FUNDAMENTALS

System Components

Local exhaust ventilation systems typically consist of the following basic elements:

- Hood to capture pollutants and/or excessive heat
- Ducted system to transport polluted air to air cleaning device or building exhaust
- Air-cleaning device to remove captured pollutants from the airstream for recycling or disposal
- Air-moving device (e.g., fan or high-pressure air ejector), which provides motive power to overcome system resistance
- Exhaust stack, which discharges system air to the atmosphere

System Classification

Contaminant Source Type. Knowledge of the process or operation is essential before a local exhaust hood system can be designed.

The preparation of this chapter is assigned to TC 5.8, Industrial Ventilation Systems.

Hood Type. Exhaust hoods are typically round, rectangular, or slotted to accommodate the geometry of the source. Hoods are either enclosing or nonenclosing (Figure 1). **Enclosing hoods** provide more effective and economical contaminant control because their exhaust rates and the effects of room air currents are minimal compared to those for nonenclosing hoods. Hood access openings for inspection and maintenance should be as small as possible and out of the natural path of the contaminant. Hood performance (i.e., how well it captures the contaminant) must be verified by an industrial hygienist.

A **nonenclosing hood** can be used if access requirements make it necessary to leave all or part of the process open. Careful attention must be paid to airflow patterns and capture velocities around the process and hood and to the process characteristics to make nonenclosing hoods effective. The more of the process that can be enclosed, the less exhaust airflow required to control the contaminant(s).

System Mobility. Local exhaust systems with nonenclosing hoods can be **stationary** (i.e., having a fixed hood position), **moveable, portable, or built-in** (into the process equipment). Moveable hoods are used when process equipment must be accessed for repair and loading and unloading of materials (e.g., in electric ovens for melting steel).

The portable exhaust system shown in Figure 2 is commonly used for temporary exhausting of fumes and solvents in confined spaces or during maintenance. It has a built-in fan and filter and a linear or round exhaust hood connected to a flexible hose. Built-in local exhausts are commonly used to evacuate welding fumes, such as hoods built into stationary or turnover welding tables. Lateral

exhaust hoods, which exhaust air through slots on the periphery of open vessels, such as those used for galvanizing metals, are examples of built-in local exhausts.

Effectiveness of Local Exhaust

The most effective hood uses the minimum exhaust airflow rate to provide maximum contaminant control. **Capture effectiveness** should be high, but it can be difficult and costly to develop a hood that is 100% efficient. Makeup air supplied by general ventilation to replace exhausted air can dilute contaminants that are not captured by the hood. The more of the process that can be enclosed, the less exhaust airflow required to control the contaminant(s).

Capture Velocity. Capture velocity is the air velocity at the point of contaminant generation upstream of a hood. The contaminant enters the moving airstream at the point of generation and is carried along with the air into the hood. Designers use a capture velocity V_c to select a volumetric flow rate to draw air into the hood. Table 1 shows ranges of capture velocities for several industrial operations. These figures are based on successful experience under ideal conditions. Once capture velocity upstream of the hood and hood position relative to the source are known, then the hood flow rate can be determined for the particular hood design. Velocity distributions for specific hoods must be known or determined.

Hood Volumetric Flow Rate. For a given hood configuration and capture velocity, the exhaust volumetric flow rate (the airflow rate that allows contaminant capture) can be calculated as

$$Q_o = V_o A_o \qquad (1)$$

where

    Q_o = exhaust volumetric flow rate, cfm
    V_o = average air velocity in hood opening that ensures capture velocity at point of contaminant release, fpm
    A_o = hood opening area, ft^2

Low face velocities require that supply (makeup) air be as uniformly distributed as possible to minimize the effects of room air currents. This is one reason replacement air systems must be designed with exhaust systems in mind. Air should enter the hood uniformly; interior baffles are sometimes necessary (Figure 3).

Airflow requirements for maintaining effective capture velocity at a contaminant source also vary with the distance between the source and hood. Chapter 3 of ACGIH (2004) provides methodology
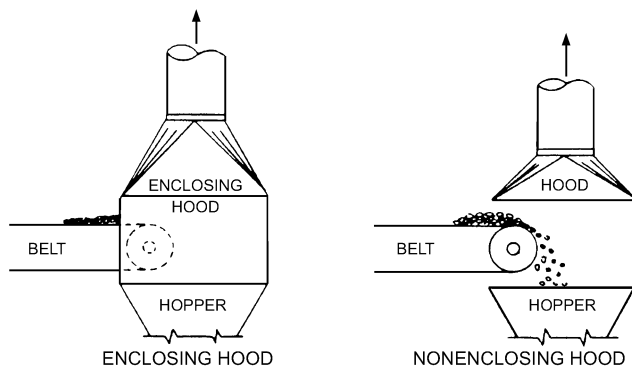
Fig. 1 Enclosing and Nonenclosing Hoods
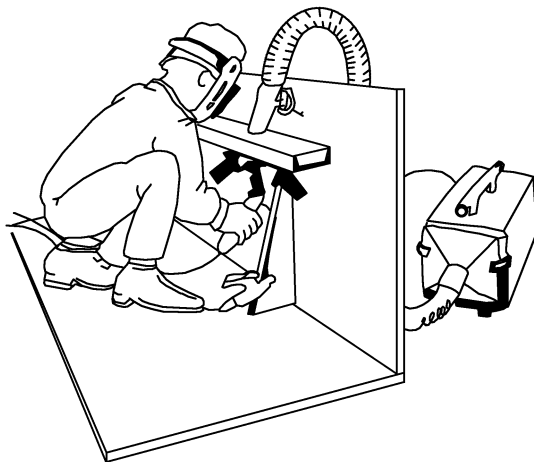
Fig. 2 Portable Fume Extractor with Built-in Fan and Filter

Table 1 Range of Capture (Control) Velocities

Condition of Contaminant Dispersion	Examples	Capture Velocity, fpm
Released with essentially no velocity into still air	Evaporation from tanks, degreasing, plating	50 to 100
Released at low velocity into moderately still air	Container filling, low-speed conveyor transfers, welding	100 to 200
Active generation into zone of rapid air motion	Barrel filling, chute loading of conveyors, crushing, cool shakeout	200 to 500
Released at high velocity into zone of very rapid air motion	Grinding, abrasive blasting, tumbling, hot shakeout	500 to 2000

Note: In each category above, a range of capture velocities is shown. The proper choice of values depends on several factors (Alden and Kane 1982):

Lower End of Range	Upper End of Range
1. Room air currents favorable to capture	1. Distributing room air currents
2. Contaminants of low toxicity or of nuisance value only	2. Contaminants of high toxicity
3. Intermittent, low production	3. High production, heavy use
4. Large hood; large air mass in motion	4. Small hood; local control only

for estimating airflow requirements for specific hood configurations and locations relative to the contaminant source.

Airflow near the hood can be influenced by drafts from supply air jets (spot cooling jets) or by turbulence of the ambient air caused by jets, upward/downward convective flows, moving people, and drafts from doors and windows. Process equipment may be another source of air movement. For example, high-speed rotating machines such as pulverizers, high-speed belt material transfer systems, falling granular materials, and escaping compressed air from pneumatic tools all produce air currents. These factors can significantly reduce the capturing effectiveness of local exhausts and should be accounted for in exhaust system design.

Exhausted air may contain combustible pollutant/air mixtures. If it does, the amount by which the exhaust airflow rate should be increased to dilute combustible mixture must be verified to meet the requirements of National Fire Protection Association (NFPA) *Standard* 86.

Principles of Hood Design Optimization

Numerous studies of local exhaust and common practices have led to the following hood design principles:

- Hood location should be as close as possible to the source of contamination.
- The hood opening should be positioned so that it causes the contaminant to deviate the least from its natural path.
- The hood should be located so that the contaminant is drawn away from the operator's breathing zone.
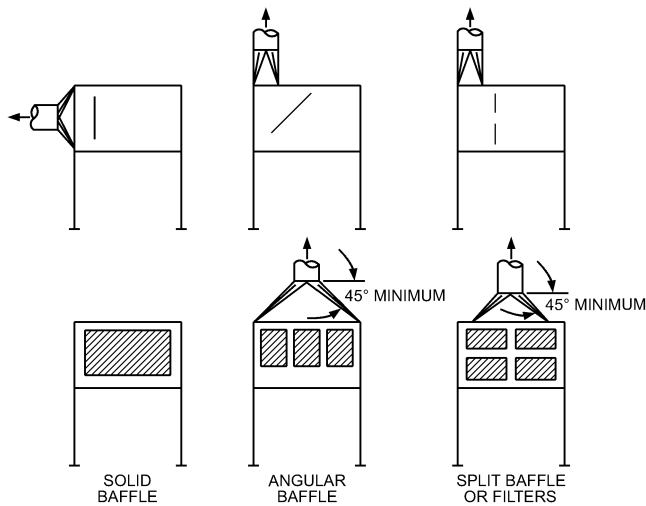
Fig. 3   Use of Interior Baffles to Ensure Good Air Distribution
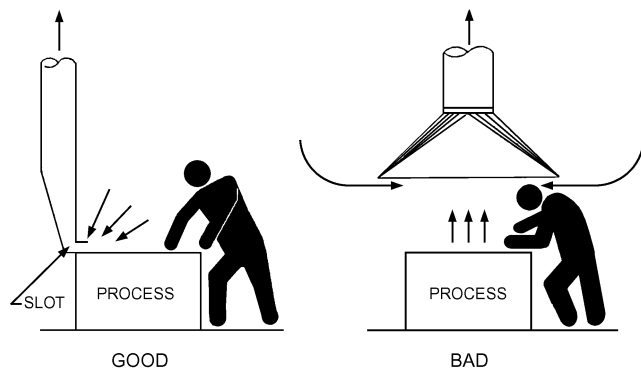
Fig. 4   Influence of Hood Location on Contamination of Air in the Operator's Breathing Zone

- Hood size must be the same as or larger than the cross section of flow entering the hood. If the hood is smaller than the flow, a higher volumetric flow rate is required.
- Worker position with relation to contaminant source, hood design, and airflow path should be evaluated on based on the principles given in Chapters 3 and 10 of ACGIH (2004).
- Canopy hoods (Figure 4) should not be used where the operator must bend over a tank or process (ACGIH 2004).

AIR MOVEMENT IN VICINITY OF LOCAL EXHAUST

Air velocities in front of the hood opening depend on the exhaust airflow rate, hood geometry, and surfaces surrounding the hood opening. Figure 5 shows velocity contours for an unflanged round duct hood. Studies have established the similarity of velocity contours (expressed as a percentage of the hood entrance velocity) for hoods with similar geometry (DallaValle 1952). Figure 6 shows velocity contours for a rectangular hood with an **aspect ratio** (width divided by length) of 0.333. The profiles are similar to those for the round hood but are more elongated. If the aspect ratio is lower than about 0.2 (0.15 for flanged openings), the flow pattern in front of the hood changes from approximately spherical to approximately cylindrical. Velocity decreases rapidly with distance from the hood.

The design engineer should consider side drafts and other sources of air movement close to the capture area of a local exhaust hood. Caplan and Knutson (1977, 1978) found that air movement in front of laboratory hoods can cause contaminants to escape from the hood and into the operator's breathing zone. In industrial applications, it is common to see large fans blowing air on workers in front of the hood. This can render the local exhaust hood ineffective to the point that no protection is provided for the worker.

Pressure Loss in Hoods and Ducts

A vena contracta forms in the entrance of the hood or duct and produces a pressure loss, which can be described using pressure loss coefficient C_o or a static pressure entry loss (ACGIH 2004). When air enters a hood, the pressure loss, called **hood entry loss**, may
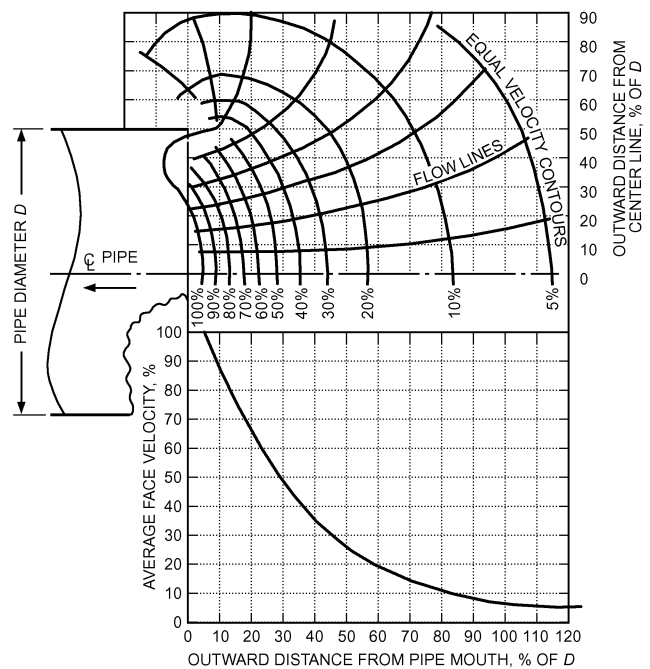
Fig. 5   Velocity Contours for Plain Round Opening
(Alden and Kane 1982; used by permission)
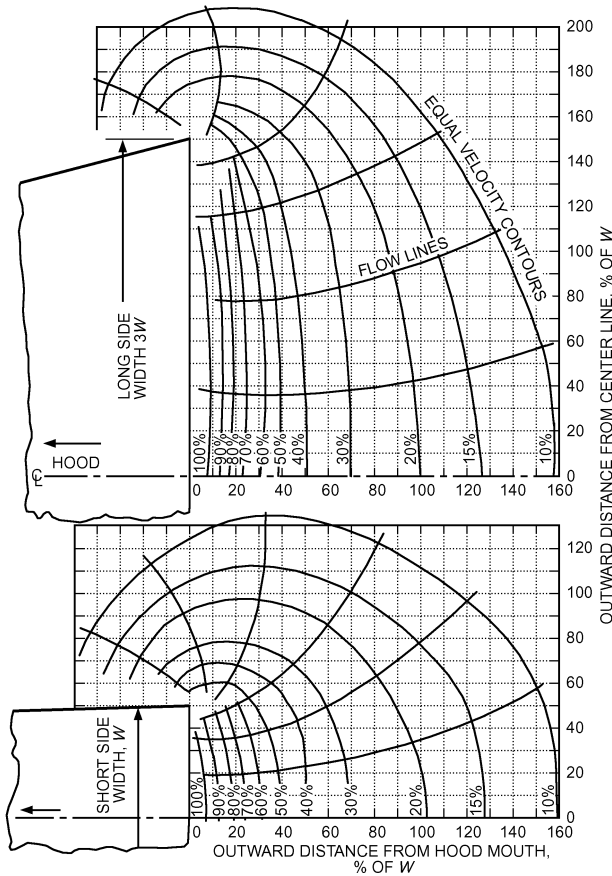
Fig. 6 Velocity Contours for Plain Rectangular Opening with Sides in a 1:3 Ratio
(Alden and Kane 1982; used by permission)

have several components, depending on the hood's complexity. Simple hoods usually have a single pressure loss coefficient specified, defined as

$$C_L = \sqrt{\frac{P_v}{P_{s,h}}} \qquad (2)$$

where

C_L = loss factor depending on hood type and geometry, dimensionless

$P_v = K\rho V^2/2g_c$, dynamic pressure inside duct (constant in duct after vena contracta) where K is proportionality constant, in. of water, ρ is air density in lb/ft^3, and g_c is the gravitational acceleration constant, 32.2 $lb_m \cdot ft/lb_f \cdot s^2$

$P_{s,h}$ = static pressure in hood duct because of velocity pressure increase and hood entry loss, in. of water

More information on loss factors and the design of exhaust ductwork is in Chapter 35 of the 2005 *ASHRAE Handbook—Fundamentals*, ACGIH (2004), and Brooks (2001).

The loss coefficient C_L is different from the hood entry loss coefficient. The entry loss coefficient C_o relates duct total pressure loss to duct velocity pressure. From Bernoulli's equation, hood total pressure is approximately zero at the entrance to the hood, and therefore the static pressure is equal to the negative of the velocity pressure:

$$P_s = -P_v \qquad (3)$$

Static pressure in the hood/duct is the static pressure (velocity pressure) plus the head loss, which is expressed as a fraction of the velocity pressure, as
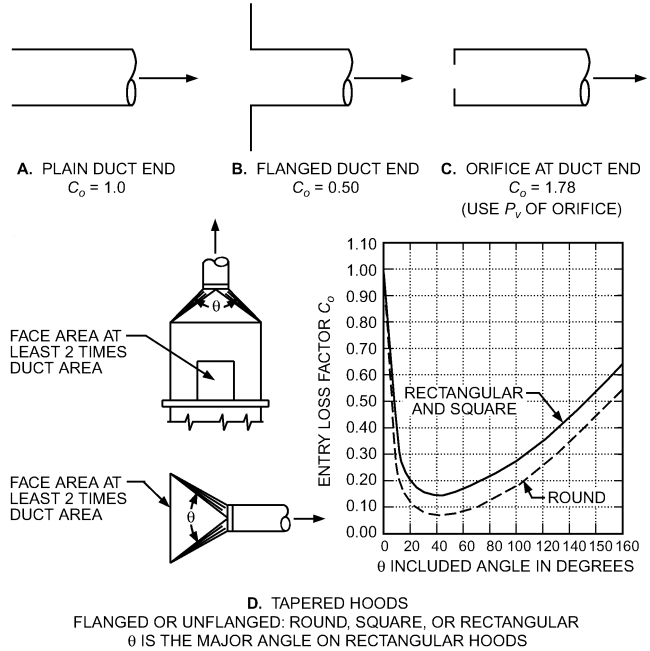
Fig. 7 Entry Losses for Typical Hoods
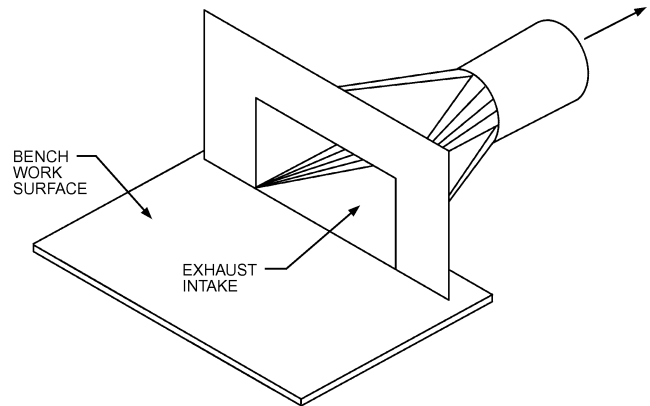
Fig. 8 Hood on Bench

$$P_{s,h} = P_v + C_o P_v \qquad (4)$$

Rearranged, the hood/duct static pressure $P_{s,h}$ (hood suction) for hoods is

$$P_{s,h} = (1 + C_o)P_v \qquad (5)$$

and the change in total pressure is

$$\Delta P_t = P_{s,h} - P_v = C_o P_v \qquad (6)$$

Loss coefficients C_o for various hood shapes are given in Figure 7. For tapered hoods, Figure 5 shows that the optimum hood entry angle to minimize entry loss is 45°, but this may be impractical in many situations because of the required transition length. A 90° angle, with a corresponding loss factor of 0.25 (for rectangular openings), is typical for many tapered hoods.

Example 1. A nonenclosing side-draft flanged hood (Figure 8) with face dimensions of 1.5 by 4 ft rests on the bench. The required volumetric flow rate is 1560 cfm. The duct diameter is 9 in.; this gives a duct velocity of 3530 fpm. The hood is designed such that the largest angle of transition between the hood face and the duct is 90°. What is the suction pressure (static pressure) for this hood? Assume air density at 72°F.
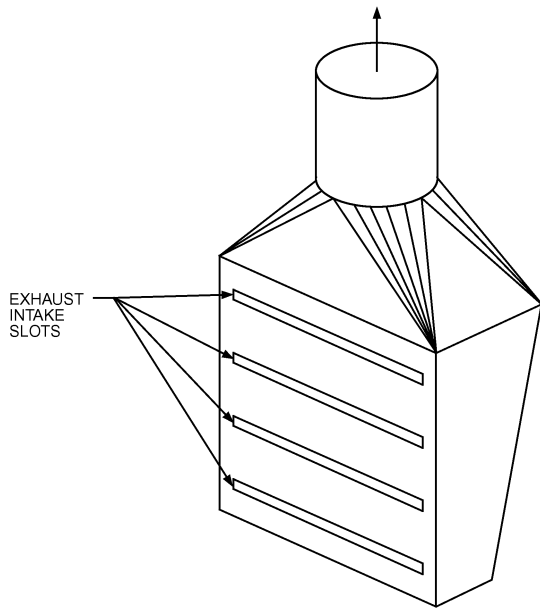
Fig. 9 Multislot Nonenclosing Hood

Solution: The two transition angles cannot be equal. Whenever this is true, the larger angle is used to determine the loss factor from Figure 6. Because the transition piece originates from a rectangular opening, the curve marked "rectangular" must be used. This corresponds to a loss factor of 0.25. The duct velocity pressure is

$$P_v = \frac{\rho V^2}{2g_c} = \frac{(0.075)(3530)^2}{(2)(32.2)} \times \frac{12}{(62.4)(3600)} = 0.78 \text{ in. of water}$$

From Equation (5),

$$P_{s,h} = (1 + 0.25)(0.78) = 0.98 \text{ in. of water}$$

Compound Hoods. Losses for multislot hoods (Figure 9) or single-slot hoods with a plenum (compound hoods) must be analyzed somewhat differently. The slots distribute air over the hood face and do not influence capture efficiency. Slot velocity should be approximately 2000 fpm to provide required distribution at minimum energy cost; plenum velocities are typically 50% of slot velocities (approximately 1000 fpm). Higher velocities dissipate more energy and can cause hot spots in the face of the hood.

Losses occur when air passes through the slot and when air enters the duct. Because the velocities, and therefore the velocity pressures, can be different at the slot and at the duct entry locations, the hood suction must reflect both losses and is given by

$$P_{s,h} = P_v + (C_o P_v)_s + (C_o P_v)_d \tag{7}$$

where the first P_v is generally the higher of the two velocity pressures, s refers to the slot, and d refers to the duct entry location.

Example 2. A multislot hood has three slots, each 1 by 40 in. At the top of the plenum is a 90° transition into the 10 in. duct. The volumetric flow rate required for this hood is 1650 cfm. Determine the hood suction (static pressure). Assume air density at 72°F.

Solution: The slot velocity V_s is

$$V_s = \frac{(1650)(144)}{(3)(40)(1)} = 1980 \text{ fpm}$$

which is near the minimum slot velocity of 2000 fpm. Substituting this velocity,

A. SIDEDRAFT HOOD   B. SLOT HOOD
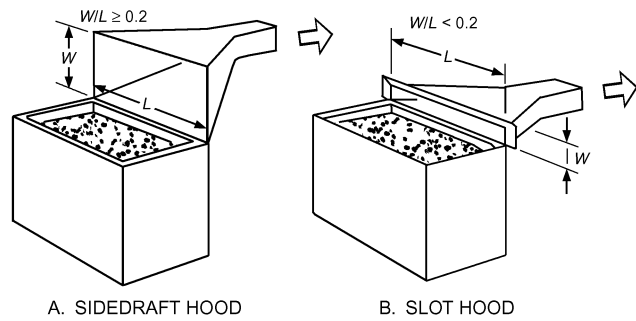
Fig. 10 Sidedraft Hood and Slot Hood on Tank

$$P_v = \frac{\rho V^2}{2g} = \frac{(0.075)(1980)^2}{(2)(32.2)} \times \frac{(12)}{(62.4)(3600)} = 0.24 \text{ in. of water}$$

The duct area is 0.5454 ft². Therefore, duct velocity and velocity pressure are

$$V_d = \frac{1650}{0.5454} = 3025 \text{ fpm}$$

Substituting this velocity,

$$P_v = \frac{(0.075)(3025)^2}{(2)(32.2)} \times \frac{(12)}{(62.4)(3600)} = 0.57 \text{ in. of water}$$

For a 90° transition into the duct, the loss factor is 0.25. For the slots, the loss factor is 1.78 (Figure 6). The duct velocity pressure is added to the sum of the two losses because it is larger than the slot velocity pressure. Using Equation (5),

$$P_{s,h} = 0.57 + (1.78)(0.24) + (0.25)(0.57) = 1.14 \text{ in. of water}$$

Exhaust volume requirements, minimum duct velocities, and entry loss factors for many specific operations are given in Chapter 10 of ACGIH (2004).

Overhead Hoods

If the process cannot be completely enclosed, the canopy hood should be placed above the process so that the contaminant moves toward the hood. Canopy hoods should be applied and designed with caution to avoid drawing contaminants across the operator's breathing zone (see Figure 6). The hood's height above the process should be minimized to reduce total exhaust airflow rate.

Sidedraft Hoods

Sidedraft hoods typically draw contaminant away from the operator's breathing zone. With a buoyant source, a sidedraft hood requires a higher exhaust volumetric flow rate than a low canopy hood. If a low canopy hood restricts operation, a sidedraft hood may be more cost-effective than a high canopy hood. Examples of sidedraft hoods include multislotted "pickling" hoods near welding benches (Figure 9), flanged hoods, and slot hoods on tanks (Figure 10).

OTHER LOCAL EXHAUST SYSTEM COMPONENTS

Duct Design and Construction

Duct Considerations. The second component of a local exhaust ventilation system is the duct through which contaminated air is transported from the hood(s). Round ducts are preferred because they (1) offer more uniform velocity to resist settling of material and (2) can withstand the higher static pressures normally found in exhaust systems. When design limitations require rectangular or flat oval ducts, the aspect ratio (height-to-width ratio) should be as close to unity as possible.

Table 2   Contaminant Transport Velocities

Nature of Contaminant	Examples	Minimum Transport Velocity, fpm
Vapor, gases, smoke	All vapors, gases, smoke	Usually 1000 to 2000
Fumes	Welding	2000 to 2500
Very fine light dust	Cotton lint, wood flour, litho powder	2500 to 3000
Dry dusts and powders	Fine rubber dust, molding powder dust, jute lint, cotton dust, shavings (light), soap dust, leather shavings	3000 to 4000
Average industrial dust	Grinding dust, buffing lint (dry), wool jute dust (shaker waste), coffee beans, shoe dust, granite dust, silica flour, general material handling, brick cutting, clay dust, foundry (general), limestone dust, asbestos dust in textile industries	3500 to 4000
Heavy dust	Sawdust (heavy and wet), metal turnings, foundry tumbling barrels and shakeout, sand-blast dust, wood blocks, hog waste, brass turnings, cast-iron boring dust, lead dust	4000 to 4500
Heavy and moist dust	Lead dust with small chips, moist cement dust, asbestos chunks from transite pipe cutting machines, buffing lint (sticky), quicklime dust	4500 and up

Source: From American Conference of Governmental Industrial Hygienists (ACGIH®), *Industrial Ventilation: A Manual of Recommended Practice*, 25th ed. Copyright 2004. Reprinted with permission.

Minimum transport velocity is the velocity required to transport particles without settling. Table 2 lists some generally accepted transport velocities as a function of the nature of the contaminants (ACGIH 2004). The values listed are typically higher than theoretical and experimental values to account for (1) damage to ducts, which increases system resistance and reduces volumetric flow and duct velocity; (2) duct leakage, which tends to decrease velocity in the duct system upstream of the leak; (3) fan wheel corrosion or erosion and/or belt slippage, which could reduce fan volume; and (4) reentrainment of settled particles caused by improper operation of the exhaust system. Design velocities can be higher than minimum transport velocities but should never be significantly lower.

When particle concentrations are low, the effect on fan power is negligible. Standard duct sizes and fittings should be used to cut cost and delivery time. Information on available sizes and cost of nonstandard sizes can be obtained from the contractor(s).

Duct Losses. Chapter 35 of the 2005 *ASHRAE Handbook—Fundamentals* covers the basics of duct design and design of metalworking exhaust systems. The design method presented there is based on total pressure loss, including fitting coefficients; ACGIH (2004) calculates static pressure loss. Loss coefficients are found in Chapter 35 of the 2005 *ASHRAE Handbook—Fundamentals* and in the ASHRAE *Duct Fitting Database* CD-ROM (ASHRAE 2002).

For systems conveying particles, elbows with a centerline radius-to-diameter ratio *(r/D)* greater than 1.5 are the most suitable. If $r/D \leq 1.5$, abrasion in dust-handling systems can reduce the life of elbows. Elbows, especially those with large diameters, are often made of seven or more gores. For converging flow fittings, a 30° entry angle is recommended to minimize energy losses and abrasion in dust-handling systems (Fitting ED5-1 in Chapter 35 of the 2005 *ASHRAE Handbook—Fundamentals*).

Where exhaust systems handling particles must allow for a substantial increase in future capacity, required transport velocities can be maintained by providing open-end stub branches in the main duct. Air is admitted through these stub branches at the proper pressure and volumetric flow rate until the future connection is installed. Figure 11 shows such an air bleed-in. Using outside air minimizes replacement air requirements. The size of the opening can be calculated by determining the pressure drop required across the orifice from the duct calculations. Then the orifice velocity pressure can be determined from one of the following equations:

$$P_{v,o} = \frac{\Delta P_{t,o}}{C_o} \tag{8}$$

or

$$P_{v,o} = \frac{\Delta P_{s,o}}{C_o + 1} \tag{9}$$

where

$P_{v,o}$ = orifice velocity pressure, in. of water
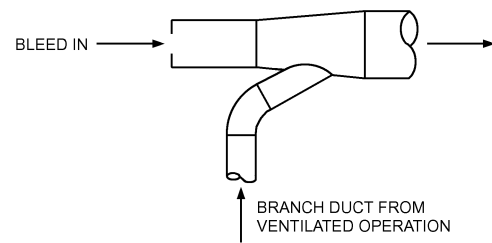
Fig. 11   Air Bleed-In

ΔT_o = total pressure to be dissipated across orifice, in. of water
$\Delta P_{s,o}$ = static pressure to be dissipated across orifice, in. of water
C_o = orifice loss coefficient referenced to the velocity at the orifice cross-sectional area, dimensionless (see Figure 6)

Equation (8) should be used if total pressure through the system is calculated; Equation (9) should be used if static pressure through the system is calculated. Once the velocity pressure is known, orifice velocity and size can be determined.

Occasionally, a counterweighted backdraft damper or spring-loaded air admittance valve, configured to allow airflow into the duct but not out, is used as an air bleed in lieu of an orifice in systems that operate under varying airflow conditions. This ensures the proper quantity of transport airflow inside the duct, helping to eliminate material fallout and subsequent duct blockage.

Integrating Duct Segments. Most systems have more than one hood. If the pressures are not designed to be the same for merging parallel airstreams, the system adjusts to equalize pressure at the common point; however, the flow rates of the two merging airstreams will not necessarily be the same as designed. As a result, the hoods can fail to control the contaminant adequately, exposing workers to potentially hazardous contaminant concentrations. Two design methods ensure that the two pressures will be equal. The preferred design self-balances without external aids. This procedure is described in the section on Industrial Exhaust System Duct Design in Chapter 35 of the 2005 *ASHRAE Handbook—Fundamentals*. The second design, which uses adjustable balance devices such as blast gates or balancing dampers, is not recommended, especially when abrasive material is conveyed.

Duct Construction. Elbows and converging flow fittings should be made of thicker material than the straight duct, especially if abrasives are conveyed. Elbows with $r/D > 2$ with replaceable wear plates (wear backs) in the heel are often used where particulate loading is extremely heavy or the particles are very abrasive. When corrosive material is present, alternatives such as special coatings or different duct materials (fibrous glass or stainless steel) can be used. Cleanout openings should be located to allow access to the duct interior in the event of a blockage. Certain contaminants may require

washdown systems and/or fire detection and suppression systems to comply with safety or fire prevention codes. These requirements should be verified with local code officials and insurance underwriters. NFPA standards provide guidance on fire safety. Industrial duct construction is described in Chapter 16 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*, and in the Sheet Metal and Air Conditioning Contractors' National Association's *Round Industrial Duct Construction Standards* (SMACNA 1999).

Air Cleaners

Air-cleaning equipment is usually selected to (1) conform to federal, state, or local emissions standards and regulations; (2) prevent re-entrainment of contaminants to work areas; (3) reclaim usable materials; (4) permit cleaned air to recirculate to work spaces and/or processes; (5) prevent physical damage to adjacent properties; and (6) protect neighbors from contaminants.

Factors to consider when selecting air-cleaning equipment include the type of contaminant (number of components, particulate versus gaseous, moisture and heat in the airstream, and pollutant concentration), required contaminant removal efficiency, disposal method, and air or gas stream characteristics. Auxiliary systems such as instrument-grade compressed air, electricity, or water may be required and should be considered in equipment selection. Specific hazards such as explosions, fire, or toxicity must be considered in equipment selection, design, and location. See Chapters 24 and 25 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment* for information on equipment for removing airborne contaminants. A qualified applications engineer should be consulted when selecting equipment.

The cleaner's pressure loss must be added to overall system pressure calculations. In some cleaners, specifically some fabric filters, loss increases as operation time increases. System design should incorporate the maximum pressure drop of the cleaner, or hood flow rates will be lower than designed during most of the duty cycle. Also, fabric collector losses are usually given only for a clean air plenum. A reacceleration to the duct velocity, with the associated entry losses, must be calculated during design. Most other cleaners are rated flange-to-flange with reacceleration included in the loss.

Air-Moving Devices

The type of air-moving device selected depends on the type and concentration of contaminant, the pressure rise required, and allowable noise levels. Fans are usually used. Chapter 18 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment* describes available fans; Air Movement and Control Association (AMCA) *Publication* 201 describes proper connection of the fan(s) to the system. The fan should be located downstream of the air cleaner whenever possible to (1) reduce possible abrasion of the fan wheel blades and (2) create negative pressure in the air cleaner so that air leaks into it and positive control of the contaminant is maintained.

Fans handling flammable or explosive dusts should be specified as spark-resistant. AMCA provides three different spark-resistant fan construction specifications. The fan manufacturer should be consulted when handling these materials. Multiple NFPA standards give fire safety requirements for fans and systems handling explosive or flammable materials.

When possible, devices such as fans and pollution-control equipment should be located outside classified areas, and/or outside the building, to reduce the risk of fire or explosion.

In some instances, the fan is located upstream from the cleaner to help remove dust. This is especially true with cyclone collectors, for example, which are used in the woodworking industry. If explosive, corrosive, flammable, or sticky materials are handled, an injector can transport the material to the air-cleaning equipment. Injectors create a shear layer that induces airflow into the duct. Injectors should be the last choice because their efficiency seldom exceeds 10%.

Energy Recovery

Energy transfer from exhausted air to replacement air may be economically feasible, depending on the (1) location of the exhaust and replacement air ducts, (2) temperature of the exhausted gas, and (3) nature of the contaminants being exhausted. Heat transfer efficiency depends on the type of heat recovery system used.

If exhausted air contains particulate matter (e.g., dust, lint) or oil mist, the exhausted air should be filtered to prevent fouling the heat exchanger. If exhausted air contains gaseous and vaporous contaminants, such as hydrocarbons and water-soluble chemicals, their effect on the heat recovery device should be investigated. Chapter 44 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment* covers energy recovery.

When selecting energy recovery equipment for industrial exhaust systems, cross-contamination from the energy recovery device must be considered. Some types of energy recovery equipment may allow considerable cross-contamination (e.g., heat wheels) from the exhaust into the supply airstream, whereas other types (e.g., runaround coils) do not. The exhaust side of the energy recovery device should be negatively pressured compared to the supply side, so that any leakage will be from the clean side into the contaminated side. This is not acceptable for some applications. The material of the energy recovery device must be compatible with the gases being exhausted. If the exhaust airstream destroys the heat exchanger, contamination can enter the supply airstream and cause the same type of equipment damage as well as increase exposure to workers.

Exhaust Stacks

The exhaust stack must be designed and located to prevent reentraining discharged air into supply system inlets. The building's shape and surroundings determine the atmospheric airflow over it. Chapter 16 of the 2005 *ASHRAE Handbook—Fundamentals* and Chapter 44 of this volume cover exhaust stack design. The typical code minimum required stack height is to provide protection for workers near the stack, so discharged air will be above their breathing zone. The minimum required stack height does not protect against reentrainment of contaminated exhaust into any outside air intakes.

If rain protection is important, a no-loss stack head design (ACGIH 2004; SMACNA *Standard* 005-1999) is recommended. Weather caps deflect air downward, increasing the chance that contaminants will recirculate into air inlets; have high friction losses; and provide less rain protection than a properly designed stack head. Weather caps should never be used with a contaminated or hazardous exhaust stream.

Figure 12 contrasts flow patterns of weather caps and stack heads. Loss data for stack heads are presented in the *Duct Fitting*
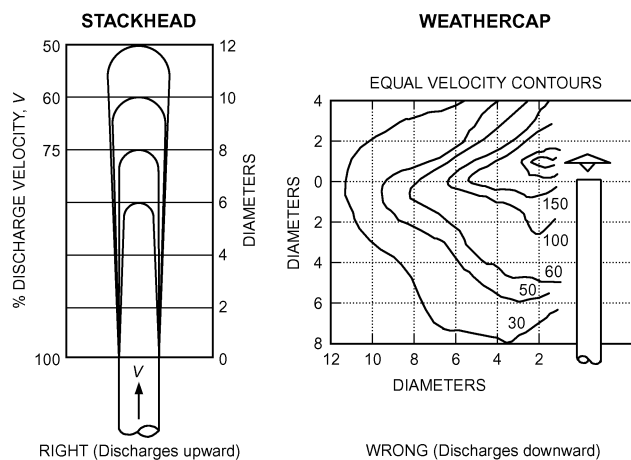
Fig. 12   Comparison of Flow Pattern for Stackheads and Weathercaps

Database CD-ROM (ASHRAE 2006). Losses in straight-duct stack heads are balanced by the pressure regain at the expansion to the larger-diameter stack head.

Instrumentation and Controls

Some industrial exhaust systems may require positive verification of system airflow. Other instrumentation, such as dust collector level indication, rotary lock valve operation, or fire detection, may be required. Interfaces may be required with the process control system or with the balance of the plant ventilation system. Electrical devices in systems conveying flammable or explosive materials or in a hazardous location may need to meet certain electrical safety and code requirements. These requirements are determined by the owner, process equipment manufacturer, federal and state regulations, local codes, and/or insurance requirements.

OPERATION

System Testing and Balancing

After installation, an exhaust system should be tested and balanced to ensure that it operates properly, with the required flow rates through each hood. If actual flow rates are different from design values, they should be corrected before the system is used. Testing is also necessary to obtain baseline data to determine (1) compliance with federal, state, and local codes; (2) by periodic inspections, whether maintenance on the system is needed to ensure design operation; (3) whether a system has sufficient capacity for additional airflow; (4) whether system leakage is acceptable; and (5) compliance with testing, adjusting, and balancing (TAB) standards. AMCA *Publication* 203 and Chapter 9 of ACGIH (2004) contain detailed information on preferred methods for testing systems.

Operation and Maintenance

Periodic inspection and maintenance are required for proper operation of exhaust systems. Systems are often changed or damaged after installation, resulting in low duct velocities and/or incorrect volumetric flow rates. Low duct velocities can cause contaminants to settle and plug the duct, reducing flow rates at affected hoods. Adding hoods to an existing system can change volumetric flow at the original hoods. In both cases, changed hood volumes can increase worker exposure and health risks. The maintenance program should include (1) inspecting ductwork for particulate accumulation and damage by erosion or physical abuse, (2) checking exhaust hoods for proper volumetric flow rates and physical condition, (3) checking fan drives, (4) maintaining air-cleaning equipment according to manufacturers' guidelines, and (5) confirming that the system continues to meet compliance.

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CHAPTER 31

KITCHEN VENTILATION

KITCHEN ventilation is a complex application of HVAC systems. System design includes aspects of air conditioning, fire safety, ventilation, building pressurization, refrigeration, air distribution, and food service equipment. Kitchens are in many buildings, including restaurants, hotels, hospitals, retail malls, single- and multifamily dwellings, and correctional facilities. Each building type has special requirements for its kitchens, but many basic needs are common to all.

Kitchen ventilation has at least two purposes: (1) to provide a comfortable environment in the kitchen and (2) to enhance the safety of personnel working in the kitchen and of other building occupants. Comfort criteria often depend on the local climate, because some kitchens are not air conditioned. The ventilation system can also affect the acoustics of a kitchen. Kitchen ventilation enhances safety by removing combustion products from gas- or solid-fueled equipment.

The centerpiece of almost any kitchen ventilation system is an exhaust hood, used primarily to remove cooking effluent from kitchens. Effluent includes gaseous, liquid, and solid contaminants produced by the cooking process, and may also include products of fuel and even food combustion. These contaminants must be removed for both comfort and safety; effluent can be potentially life-threatening and, under certain conditions, flammable. The arrangement of food service equipment and its coordination with the hood(s) greatly affect kitchen operating costs.

HVAC system designers are most frequently involved in commercial kitchen applications, in which cooking effluent contains large amounts of grease or water vapor. Residential kitchens typically use a totally different type of hood. The amount of grease produced in residential applications is significantly less than in commercial applications, so the health and fire hazard is much lower.

COOKING EFFLUENT

Effluent Generation

As heat is applied to food in cooking, effluent is released into the surrounding atmosphere. This effluent includes thermal energy (as a convective plume and as heat radiated from the appliance to the kitchen space) that has not transferred to the food, water vapor, and organic material released from the food. The energy source for the appliance, especially if it involves combustion, may release additional contaminants.

All cooking methods release some heat, some of which radiates from hot surfaces, and some that is dissipated by natural convection via a rising **plume** of heated air. The fraction of appliance energy input that is released to form a thermal (convective) plume can vary from approximately 50 to 90%. Typically, most effluent released from the food and the heat source is entrained in this plume, so primary contaminant control is based on capturing and removing the air and effluent that constitute the plume by using exhaust

ventilation. However, heat radiated to the space from the appliance is largely unaffected by ventilation and must be addressed by the space air-conditioning system. Chapter 30 of the 2005 *ASHRAE Handbook—Fundamentals* lists typical space heat gain values for many commercial kitchen appliances.

Effluent from five types of commercial cooking equipment has been measured under a typical exhaust hood (Kuehn et al. 1999). Foods that emit relatively large amounts of grease were selected. Figure 1 shows the measured amount of grease in the plume entering the hood above different appliances and the amount in the vapor phase, particles below 2.5 μm in size (PM 2.5), particles less than 10 μm in size (PM 10), and the total amount of particulate grease. Ovens and fryers generate little or no grease particulate emissions, whereas other processes generate significant amounts. However, underfired broilers generate much smaller particulates compared to the griddles and ranges, and these emissions depend on the broiler design. The amount of grease in the vapor phase is significant and varies from 30% to over 90% by mass; this affects the design approach for grease removal systems.

Carbon monoxide (CO) and carbon dioxide (CO_2) emissions are present in solid fuel and natural gas combustion processes but not in processes from electrical appliances. Additional CO and CO_2 emissions may be generated by underfired boilers when grease drippings land on extremely hot surfaces and burn. Nitrogen oxide (NO_x) emissions appear to be exclusively associated with gas appliances and related to total gas consumption.

Figure 2 shows the measured plume volumetric flow rate entering the hood. In general, gas appliances have larger flow rates than electric because additional products of combustion must be vented. Underfired broilers have plume flow rates considerably larger than the other appliances shown. Effluent flow rates from underfired broilers are approximately 100 times larger than the actual volumetric flow rate created by vaporizing moisture and grease from food.
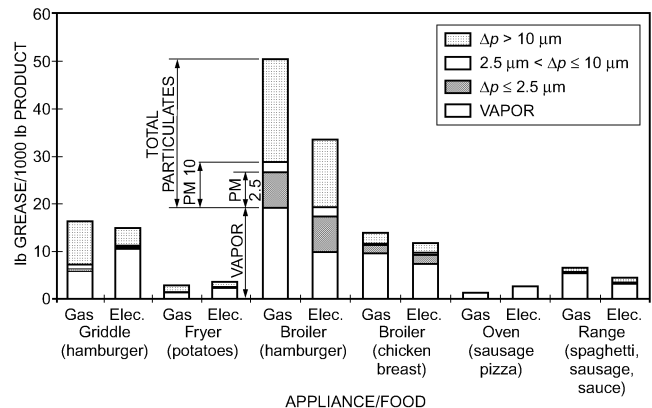
Fig. 1   Grease in Particle and Vapor Phases Emitted by
Selected Commercial Cooking Appliances and Food Products
(Kuehn et al. 1999)

The preparation of this chapter is assigned to TC 5.10, Kitchen Ventilation.

The difference is caused by ambient air entrained into the effluent plume before it reaches the exhaust hood.

Thermal Plume Behavior

The most common method of contaminant control is to install an air inlet device (a hood) where the plume can enter it and be conveyed away by an exhaust system. The hood is generally located above or behind the heated surface to intercept normal upward flow. Understanding plume behavior is central to designing effective ventilation systems.

Effluent released from a noncooking cold process, such as metal grinding, is captured and removed by placing air inlets so that they catch forcibly ejected material, or by creating airstreams with sufficient velocity to induce the flow of effluent into an inlet. This technique has led to an empirical concept of **capture velocity** that is often misapplied to hot processes. Effluent (such as grease and smoke from cooking) released from a hot process and contained in a plume may be captured by locating an inlet hood so that the plume flows into it by buoyancy. Hood exhaust rate must equal or slightly exceed plume volumetric flow rate, but the hood need not actively induce capture of the effluent if the hood is large enough at its height above the cooking operation to encompass the plume as it expands during its rise. Additional exhaust airflow may be needed to resist cross currents that carry the plume away from the hood.
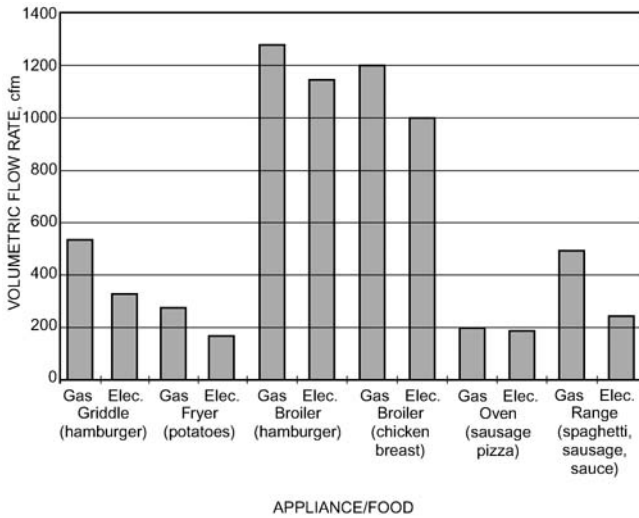
A heated plume, without cross currents or other interference, rises vertically, entraining additional air, which causes the plume to enlarge and its average velocity and temperature to decrease. If a surface parallel to the plume centerline (e.g., a back wall) is nearby, the plume will be drawn toward the surface by the **Coanda effect**. This tendency may also help direct the plume into the hood. Figure 3 illustrates a heated plume with and without cooking effluent as it rises from heated cooking appliances. Figure 3A shows two charbroilers cooking hamburgers under a wall-mounted, exhaust-only, canopy hood. Note that the hood is mounted against a clear back wall to improve experimental observation. Figures 3B and 3C show the hot air plume without cooking, visualized using a schlieren optical system, under full capture and spillage conditions, respectively.

EXHAUST HOODS

The design, engineering, construction, installation, and maintenance of commercial kitchen exhaust hoods are controlled by nationally recognized standards [e.g., National Fire Protection Association (NFPA) *Standard* 96] and model codes [e.g., *International Mechanical Code* (IMC; ICC 2006a), *International Fuel Gas Code* (IFGC; ICC 2006b)]. In some cases, local codes may prevail. Before designing a kitchen ventilation system, the designer should identify governing codes and consult the authority having jurisdiction (AHJ). Local authorities with jurisdiction may have amendments or additions to these standards and codes.

Whether a hood is required is determined by the type and quantity of emissions from cooking. Hoods are not typically required

Fig. 2   Plume Volumetric Flow Rate at Hood Entrance from Various Commercial Cooking Appliances

(Kuehn et al. 1999)
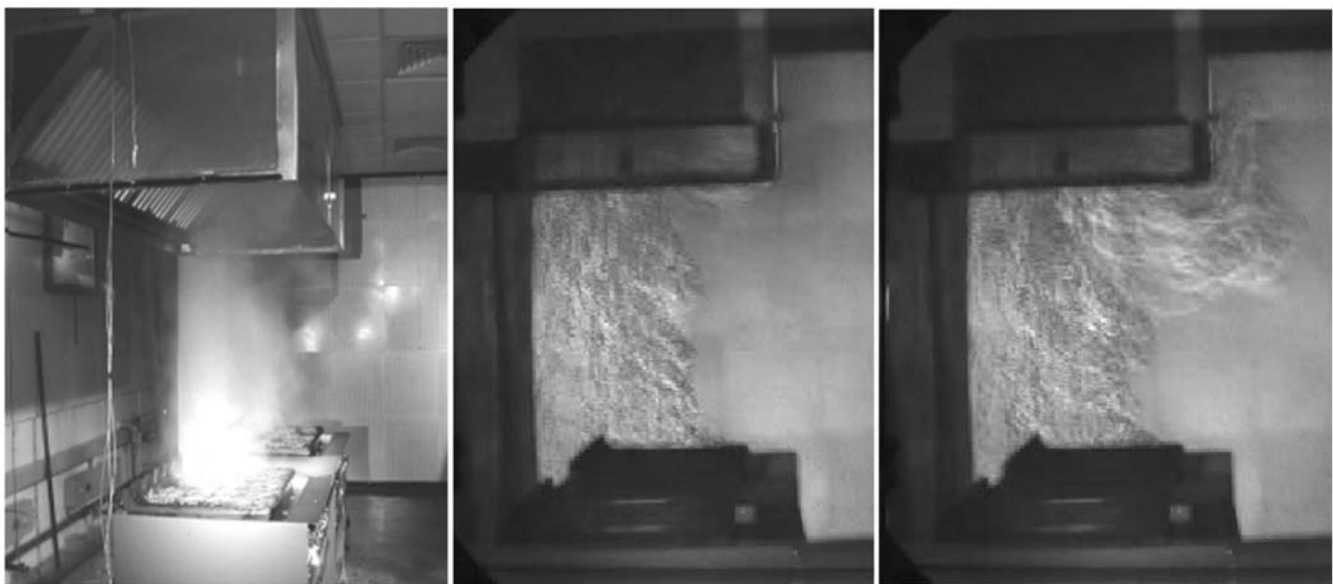
A. TEST SETUP: Two charbroilers under 8 ft long wall-mounted canopy hood, cooking hamburgers.

B. Schlieren photo of capture and containment at 4400 cfm exhaust rate. Hot, clear air visualization, no cooking.

C. Schlieren photo of spillage and containment at 3300 cfm exhaust rate. Hot, clear air visualization, no cooking.

Fig. 3   Hot-Air Plume from Cooking Appliances under Wall-Mounted Canopy Hood

over electrically heated appliances such as microwave ovens, toasters, steam tables, popcorn poppers, hot dog cookers, coffee makers, rice cookers, egg cookers, holding/warming ovens (ASHRAE *Standard* 154), or heat lamps. Appliances can be unhooded only if the additional heat and moisture loads have been considered in a thorough load calculation and accounted for in the design of the general HVAC system. Temperature and humidity in the kitchen space should be based on recommendations of ASHRAE *Standard* 55.

Hood Types

Many types, categories, and styles of hoods are available, and selection depends on many factors. Hoods are classified by whether they are designed to handle grease; Type I hoods are designed for removing grease and smoke, and Type II are not. Model codes distinguish between grease-handling and non-grease-handling hoods, but not all model codes use Type I/Type II terminology. A Type I hood may be used where a Type II hood is required, but the reverse is not allowed. However, characteristics of the equipment and processes under the hood, and not necessarily the hood type, determine the requirements for the entire exhaust system, including the hood.

A **Type I hood** is used for collecting and removing grease particulate, condensable vapor, and smoke. It includes (1) listed grease filters, baffles, or extractors for removing the grease and (2) fire-suppression system. Type I hoods are required over cooking equipment, such as ranges, fryers, griddles, broilers, and ovens, that produce smoke or grease-laden vapors.

A **Type II hood** collects and removes steam and heat where grease or smoke is not present. It may or may not have grease filters or baffles and typically does not have a fire-suppression system. It is usually used over dishwashers. A Type II hood is sometimes used over ovens, steamers, or kettles if they do not produce smoke or grease-laden vapor and if the AHJ allows it.

Type I Hoods

Categories. Type I hoods fall into two categories: unlisted and listed. **Unlisted hoods** meet the design, construction, and performance criteria of applicable national and local codes and are not allowed to have fire-actuated exhaust dampers. **Listed hoods** are listed in accordance with Underwriters Laboratories, Inc. *Standard* 710. Listed hoods are not generally designed, constructed, or operated in accordance with model code requirements, but are constructed in accordance with the terms of the hood manufacturer's listing, and are required to be installed in accordance with either NFPA *Standard* 96 or the model codes. Model codes include exceptions for listed hoods to show equivalency with the model code requirements.

The two subcategories of Type I listed hoods, as covered by UL *Standard* 710, are exhaust hoods with and without exhaust dampers. UL listings distinguish between water-wash and dry hoods. Also, water-wash hoods with fire-actuated water systems, if investigated for their suitability for fire suppression, are indicated in the UL listing.

All listed hoods are subjected to electrical (if applicable), temperature, and cooking smoke and flare-up (capture) tests. A listed exhaust hood with exhaust damper includes a fire-actuated damper, typically at the exhaust duct collar (and at the replacement air duct collar, depending on the hood configuration). In the event of a fire, the damper closes to prevent fire from entering the duct. Fire-actuated exhaust dampers are permitted only in listed hoods.

Grease Removal. Most grease removal devices in Type I hoods operate on the same general principle: exhaust air passes through a series of baffles that create a centrifugal force to throw grease particles out of the airstream as the exhaust air passes around the baffles. The amount of grease removed varies with baffle design, air velocity, temperature, type of cooking, and other factors. NFPA *Standard* 96 does not allow use of mesh-filter grease removal devices. Additionally, mesh filters cannot meet the requirements of

UL *Standard* 1046, and therefore cannot be used as primary grease filters. ASTM *Standard* F2519 provides a test method to determine the grease particle capture efficiency of commercial kitchen filters and extractors. Grease removal devices generally fall into the following categories:

- **Baffle filters** have a series of vertical baffles designed to capture grease and drain it into a container. The filters are arranged in a channel or bracket for easy insertion and removal for cleaning. Each hood usually has two or more baffle filters, which are typically constructed of aluminum, steel, or stainless steel and come in various standard sizes. Filters are cleaned by running them through a dishwasher or by soaking and rinsing. NFPA *Standard* 96 requires that grease filters be listed. Listed grease filters are tested and certified by a nationally recognized test laboratory under UL *Standard* 1046.

- **Removable extractors** (also called **cartridge filters**) have a single horizontal-slot air inlet. The filters are arranged in a channel or bracket for easy insertion and removal for cleaning. Each hood usually has two or more removable extractors, which are typically constructed of stainless steel and contain a series of horizontal baffles designed to remove grease and drain it into a container. Available in various sizes, they are cleaned by running them through a dishwasher or by soaking and rinsing. Removable extractors may be classified by a nationally recognized test laboratory under UL *Standard* 1046, or may be listed as part of the hood construction under UL *Standard* 710. Hoods that are listed with removable extractors cannot have those extractors replaced by other filters.

- **Stationary extractors** (also called a **water-wash hood**), integral to the listed exhaust hoods that use them, are typically constructed of stainless steel and contain a series of horizontal baffles that run the full length of the hood. The baffles are not removable for cleaning, though some have doors that can be removed to clean the extractors and plenum. The stationary extractor includes one or more water manifolds with spray nozzles that, when activated, wash the grease extractor with hot, detergent-injected water, removing accumulated grease. The wash cycle is typically activated at the end of the day, after cooking equipment and fans have been turned off; however, it can be activated more frequently. The cycle lasts 5 to 10 min, depending on the hood manufacturer, type of cooking, duration of operation, and water temperature and pressure. Most water-wash hood manufacturers recommend a water temperature of 130 to 180°F and water pressure of 30 to 80 psi. Average water consumption varies from 0.50 to 1.50 gpm per linear foot of hood, depending on manufacturer. Most water-wash hood manufacturers provide a manual and/or automatic means of activating the water-wash system in the event of a fire.

  Some water-wash hood manufacturers provide continuous cold water as an option. The cold water runs continuously during cooking and may or may not be recirculated, depending on the manufacturer. Typical cold water usage is 1 gph per linear foot of hood. The advantage of this method is that it improves grease extraction and removal, partly through condensation of the grease. Many hood manufacturers recommend continuous cold water in hoods located over solid-fuel-burning equipment, because the water also extinguishes hot embers that may be drawn up into the hood and helps cool the exhaust stream.

- **Multistage** extractors use two or more stages of filtration to remove a larger percentage of grease. They typically consist of a baffle filter or removable extractor followed by a higher-efficiency filter, such as a packed bead bed. Each hood usually has two or more multistage filters, which are typically constructed of aluminum or stainless steel and are available in standard sizes. Filters are cleaned by running them through a dishwasher or by soaking and rinsing. NFPA *Standard* 96 requires that grease filters be listed, so they must be tested and certified by a nationally recognized test laboratory under UL *Standard* 1046.

UL *Standards* 710 and 1046 do not include grease extraction tests. Historically, grease extraction rates published by filter and hood manufacturers are usually derived from tests conducted by independent test laboratories retained by the manufacturer. Test methods and results therefore have varied greatly.

In 2005, however, ASTM published a new grease filter test standard. ASTM *Standard* F2519 determines the grease particle capture efficiency of both removable filters and fixed extractors such as water-wash hoods. The filters are evaluated by pressure drop as well as particulate capture efficiency. The test generates a controlled quantity of oleic acid particles in size range from 0.3 to 10 μm that are released into a kitchen hood to represent the cooking effluent. The particles are than sampled and counted downstream in the ductwork with an optical particle counter, with and without the extractor in place. The difference in the counts is used to calculate the particulate capture efficiency graphed versus particle size. *Standard* F2519 measures particulate capture efficiency only, not vapor removal efficiency. A more detailed explanation is available in the Exhaust Systems section of this chapter.

Styles. Figure 4 shows the six basic hood styles for Type I applications. These style names are not used universally in all standards and codes but are well accepted in the industry. The styles are as follows:

- **Wall-mounted canopy,** used for all types of cooking equipment located against a wall.
- **Single-island canopy,** used for all types of cooking equipment in a single-line island configuration.
- **Double-island canopy,** used for all types of cooking equipment mounted back-to-back in an island configuration.
- **Back shelf/proximity,** used for counter-height equipment typically located against a wall, but possibly freestanding.
- **Eyebrow,** used for direct mounting to ovens and some dishwashers.
- **Pass-over,** used over counter-height equipment when pass-over configuration (from cooking side to serving side) is required.

Sizing. The size of the exhaust hood relative to cooking appliances is important in determining hood performance. Usually the hood must extend horizontally beyond the cooking appliances (on all open sides on canopy-style hoods and over the ends on back shelf and pass-over hoods) to capture expanding thermal currents rising from the appliances. For unlisted hoods, size and overhang requirements are dictated by the prevailing code; for listed hoods, by the terms of the manufacturer's listing. **Overhang** varies with hood style, distance between hood and cooking surface, and characteristics of cooking equipment. With back shelf and pass-over hoods, the front of the hood may be kept behind the front of the cooking equipment (**setback**) to allow head clearance for the cooks. These hoods may require a higher front inlet velocity to capture and contain expanding thermal currents. ASHRAE research indicates an appliance front overhang of 9 to 18 in. for canopy style and a 10 in. setback for back shelf/proximity style are preferable to current code minimums. All styles may have full or partial side panels to close the area between appliances and the hood. This may eliminate the side overhang requirement and generally reduces the exhaust flow rate requirement.

Exhaust Flow Rates. Exhaust flow rate requirements to capture, contain, and remove effluent vary considerably depending on hood style, overhang, distance from cooking surfaces to hood, presence and size of side panels, cooking equipment, food, and cooking processes involved. The hot cooking surfaces and product vapors create thermal air currents that are received or captured by the hood and then exhausted. The velocity of these currents depends largely on surface temperature and tends to vary from 15 fpm over steam equipment to 150 fpm over charcoal broilers. The required flow rate is determined by these thermal currents, a safety allowance to absorb cross-currents and flare-ups, and a safety factor for the style of hood.

Overhang and the presence or absence of side panels help determine the safety factor for different hood styles. Gas-fired cooking

WALL-MOUNTED CANOPY   BACK SHELF   PASS-OVER

SINGLE-ISLAND CANOPY   DOUBLE-ISLAND CANOPY   EYEBROW
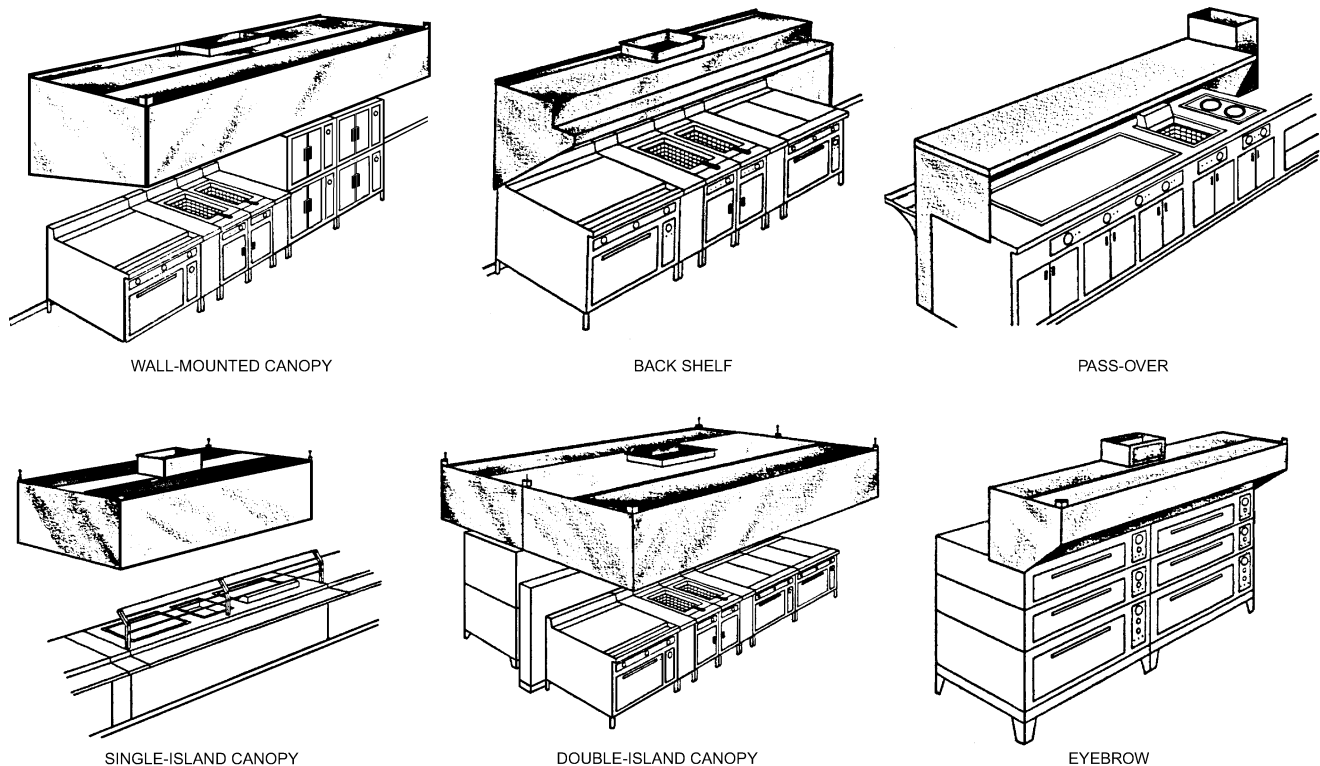
Fig. 4   Styles of Commercial Kitchen Exhaust Hoods

equipment may require an additional allowance for exhaust of combustion products and combustion air.

Because it is not practical to place a separate hood over each piece of equipment, general practice (reflected in ASHRAE *Standard* 154) is to categorize equipment into four groups, as shown in Table 1.

These categories apply to unlisted and listed Type I hoods. The exhaust volumetric flow rate requirement is based on the group of equipment under the hood. If there is more than one group, the flow rate is based on the heaviest-duty group unless the hood design allows different rates over different sections of the hood.

Though considered obsolete based on laboratory research, some local codes may still require exhaust flow rates for unlisted canopy hoods to be calculated by multiplying the horizontal area of the hood opening by a specified air velocity. Some jurisdictions may use the length of the open perimeter of the hood times the vertical height between hood and appliance instead of the horizontal hood area. Swierczyna et al. (1997) found that these methods of calculation result in higher-than-necessary exhaust flow rates for deeper

hoods, because the larger reservoirs of deeper hoods typically increase hood capture and containment performance.

Table 2 lists recommended exhaust flow rates by equipment duty category for unlisted hoods and typical design rates for listed hoods. Rates for unlisted hoods are based on ASHRAE *Standard* 154. Typical design rates for listed hoods are based on published rates for listed hoods serving single categories of equipment, which vary from manufacturer to manufacturer. Rates are usually lower for listed hoods than for unlisted hoods, and it is generally advantageous to specify listed hoods. Actual exhaust flow rates for hoods with internal short-circuit replacement air are typically higher than those in Table 2, although net exhaust rates (actual exhaust less internal replacement air quantity) are lower, which seriously compromises the hood's capture and containment performance (Brohard et al. 2003).

Listed hoods are allowed to operate at their listed exhaust flow rates by exceptions in the model codes. Most manufacturers of listed hoods verify their listed flow rates by conducting tests per UL *Standard* 710. Typically, average flow rates are much lower than those dictated by the model codes. Note that listed values are established under draft-free laboratory conditions, and actual operating conditions may compromise listed performance. Thus, manufacturers may recommend design values above their listed values.

Hoods listed in accordance with UL *Standard* 710 cover one or more cooking equipment temperatures: 400, 600 and 700°F. In application, these temperature ratings correspond to duty ratings (see Table 1). The total exhaust flow rate is typically calculated by multiplying the hood air quantity factor by hood length.

ASTM *Standard* F1704 details a laboratory flow visualization procedure for determining the capture and containment threshold of an appliance/hood system. This procedure can be applied to all hood types and configurations operating over any cooking appliances. *Standard* F2474 also provides a laboratory test procedure for determining heat gain of specific combinations of exhaust system, cooking equipment, foods, and cooking processes. Results from a series of interlab heat gain tests (Fisher 1998) have been incorporated in Chapter 30 of the 2005 *ASHRAE Handbook—Fundamentals*.

Appliance Positioning and Diversity

ASHRAE Research Project RP-1202 (Swierczyna et al. 2005) quantified the effect of the position and/or combination of appliances under an exhaust hood on the minimum capture and containment (C&C) exhaust rate. Effects of side panels, front overhang, and rear seal were also investigated. The scope of this laboratory study was to investigate similar and dissimilar appliances under a 10 ft wall-mounted canopy hood. The appliances included three full-sized electric convection ovens, three two-vat gas fryers, and three 3 ft underfired gas broilers, representing the light, medium, and

Table 1 Appliance Types by Duty Category

Light duty (400°F)	Electric or gas	Ovens (including standard, bake, roasting, revolving, retherm, convection, combination convection/steamer, conveyor, deck or deck-style pizza, pastry)
		Steam-jacketed kettles
		Compartment steamers (both pressure and atmospheric)
		Cheesemelters
		Rethermalizers
Medium duty (400°F)	Electric	Discrete element ranges (with or without oven)
	Electric or gas	Hot-top ranges
		Griddles
		Double-sided griddles
		Fryers (including open deep-fat fryers, donut fryers, kettle fryers, pressure fryers)
		Pasta cookers
		Conveyor (pizza) ovens
		Tilting skillets/braising pans
		Rotisseries
Heavy duty (600°F)	Gas Electric or gas	Open-burner ranges (with or without oven) Underfired broilers
		Chain (conveyor) broilers
		Wok ranges
		Overfired (upright) salamander broilers
Extra-heavy duty (700°F)	Appliances using solid fuel such as wood, charcoal, briquettes, and mesquite to provide all or part of the heat source for cooking.	

Table 2 Exhaust Flow Rates by Cooking Equipment Category for Unlisted and Listed Type

	Minimum Exhaust Flow Rate, cfm per linear foot of hood			
Type of Hood	**Light Duty**	**Medium Duty**	**Heavy Duty**	**Extra-Heavy Duty**
Wall-mounted canopy, unlisted	200	300	400	550
listed	150 to 200	200 to 300	200 to 400	350+
Single-island, unlisted	400	500	600	700
listed	250 to 300	300 to 400	300 to 600	550+
Double-island (per side), unlisted	250	300	400	550
listed	150 to 200	200 to 300	250 to 400	500+
Eyebrow, unlisted	250	250	Not allowed	Not allowed
listed	150 to 250	150 to 250	—	—
Back shelf/proximity/pass-over, unlisted	300	300	400	Not allowed
listed	100 to 200	200 to 300	300 to 400	Not recommended

Source: ASHRAE *Standard* 154.

Table 3 Capture and Containment Exhaust Rates for Three Like-Duty Appliance Lines at Cooking Conditions with Various Front Overhang and Side Panel Configurations under 10 ft Wall-Mounted Canopy Hood

	Best Case	Good Case	Worst Case
Three electric full-sized convection ovens	9 in. front overhang full side panels	9 in. front overhang	6 in. front overhang
	85 cfm/ft	110 cfm/ft	120 cfm/ft
Three two-vat gas fryers	18 in. front overhang partial side panels	18 in. front overhang	6 in. front overhang
	160 cfm/ft	240 cfm/ft	330 cfm/ft
Three gas broilers	12 in. front overhang partial side panels	12 in. front overhang	0 in. front overhang (6 in. cook surface)
	330 cfm/ft*	440 cfm/ft	510 cfm/ft

*Adding a rear seal between back of appliance and wall to best-case configuration (6 in. of front overhang and partial side panels) further improved hood performance to an exhaust rate of 2800 cfm (280 cfm/ft).
Source: Swierczyna et al. (2005).

heavy-duty appliance categories, respectively. In addition to various physical appliance configurations, appliances were also varied in their usage: either off, at idle conditions, or at cooking conditions. A supplemental study investigated the effect of appliance accessories (including shelving and a salamander) and hood dimensions (including hood height, depth, and reservoir volume) on the minimum exhaust rate required for complete capture and containment.

The study demonstrated that subtle changes in appliance position and hood configuration could dramatically affect the exhaust rates required for complete capture and containment, regardless of appliance duty and/or usage. The wide range in C&C values for a given hood/appliance setup explains why a similar hood installed over virtually the same appliance line may perform successfully in one kitchen and fall short of expectations in another facility. The following conclusions are specific to the conditions tested by Swierczyna et al. (2005).

Airflow Requirements for Like-Duty Appliance Lines. Evaluation supported widely accepted commercial kitchen ventilation (CKV) design practices: higher ventilation rates are required for progressively heavier-duty appliances (Table 3). For a 10 ft wall-mounted canopy hood, at a defined median or good-case installation, the light-duty oven line required 1100 cfm (110 cfm/ft), the medium-duty fryer line required 2400 cfm (240 cfm/ft), and the heavy-duty broiler line required 4400 cfm (440 cfm/ft) to achieve C&C. Simply increasing front overhang as noted between the worst- and good-case installations in Table 3 reduced the C&C exhaust rate by 10 to 27%. Installing side panels in addition to the increased front overhang (best-case scenario) reduced the exhaust requirements by an additional 18 to 33%.

Diversity in Appliance Usage. Operation diversity was evaluated with cook lines of three similar appliances and included combinations of *cook* and *off* conditions. In most cases, operation correlated directly with the required exhaust rate, with an emphasis on the operation of the end appliances (Figure 5). The capture and containment rate for the end appliance cooking and the other two like-duty appliances off was nearly the same rate as all three appliances cooking.

Changing the condition of end appliances from off to cooking had the greatest effect for medium-duty fryers, which required a 950 cfm increase in the exhaust rate. Because the fryers were thermostatically controlled, they responded to cooking operations by firing the burners. This, combined with an aggressive cooking plume, required a significantly increased exhaust rate for C&C. An aggressive thermal plume was present for the three heavy-duty broilers; the exhaust rate increased 850 cfm. For the light-duty electric convection oven, there was a 200 cfm difference in turning the end appliances from off to cook. Figure 5 also shows that cooking with only the center appliance, with the two end appliances turned off, greatly reduced the exhaust requirement.

Diversity in Appliance Duty and Position (Side-to-Side). The study found that the capture and containment rate of a multiduty
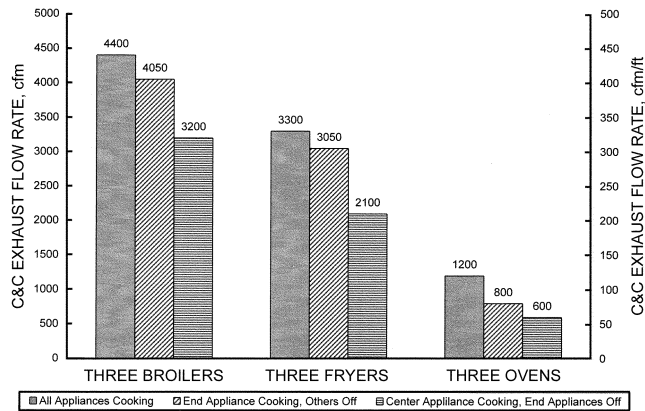
Fig. 5 Exhaust Capture and Containment Rates for One or Three Appliances Cooking from Like-Duty Classes under a 10 ft Wall-Canopy Hood
(Swierczyna et al. 2005)
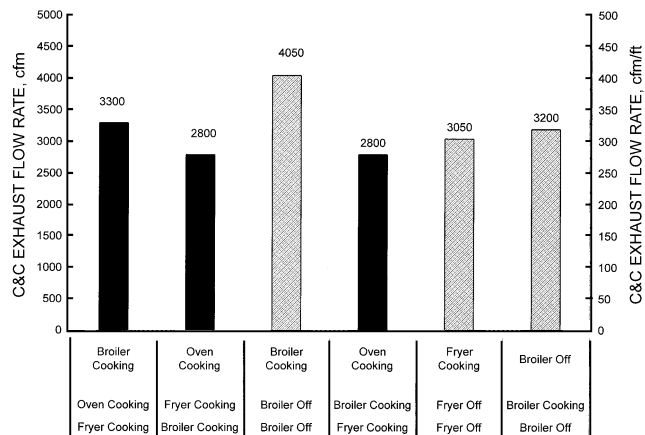
Fig. 6 Capture and Containment Exhaust Rates for Cooking Conditions on Multiduty Appliance Lines (Compared with Single-Duty Lines with Only One Appliance Operating) under 10 ft Wall Canopy Hood
(Swierczyna et al. 2005)

appliance line was less than the rate of the heaviest duty appliance in that line, applied over the length of the hood (Figure 6).

Appliance position testing confirmed the exhaust rate of an appliance line was most dependent on the duty of the end appliance.
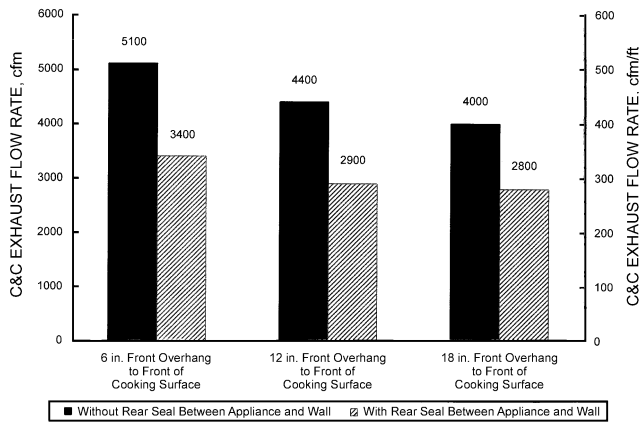
Fig. 7 Capture and Containment Exhaust Rates for Broilers under 10 ft Wall Canopy Hood With and Without Rear Appliance Seal at Various Front Overhangs
(Swierczyna et al. 2005)

Fig. 8 Exhaust Capture and Containment Rates for Three Two-Vat Gas Fryers with Various Side Panel and Overhang Configurations under 10 ft Wall Canopy Hood
(Swierczyna et al. 2005)

The end appliance drove the exhaust rate more than additional volume from the other two appliances, as they changed from off to cooking conditions or were varied in duty class. In most cases, the lowest exhaust requirements for particular appliance lines were achieved when the lowest-duty appliance was at the end of the appliance line. In other words, hood performance was optimized when the heaviest-duty appliance was in the middle of the appliance line.

Appliance Positioning (Front-to-Back) and Rear Seal. Increasing the front overhang by pushing appliances toward the back wall significantly decreased the required exhaust rates, not only because of the increased distance from the hood to the front of the appliance, but also because of the decreased distance between the back of the appliance and the wall. With a rear seal in place, some of the replacement air, which would have otherwise been drawn up from behind the appliances, was instead drawn in along the perimeter of the hood, helping guide the plume into the hood, as shown in Figure 7.

Hood Side Panels. Side panels installed on the 10 ft hood improved hood performance dramatically, by preventing the plume from spilling at the side of the hood and by increasing velocity along the front of the hood. Combining side panels (measuring 1 by 1 ft by 45°, 2 by 2 ft by 45°, 3 by 3 ft by 45°, 4 by 4 ft by 45°, or full) with the maximum hood overhang resulted in the lowest exhaust requirement for all cases tested. The example of the three two-vat gas fryer line is shown in Figure 8.

Effect of Shelving on Hood Capture and Containment Performance. Neither solid nor tubular shelving over the six-burner range required an increase in the exhaust rate. In fact, tubular shelving mounted to the back of the appliance showed a slight enhancement compared to having no shelving installed.

Effect of Hood Depth, Reservoir, and Mounting Height on Capture and Containment Performance. Comparing the 4 and 5 ft deep hoods, the deeper hood reduced capture and containment exhaust rates when appliances were positioned with maximum front overhang and minimum rear gap. The deeper hood had a negative effect when appliances remained in the minimum front overhang position. The effect of hood depth in conjunction with front overhang, side panels, and rear seal is shown in Figure 9.

Another advantage of the 5 ft over the 4 ft hood was its ability to capture and contain the plume when an oven door was opened. For a 4 ft hood and a 6 in. front overhang, an exhaust rate of 1200 cfm was required for the three electric ovens with the doors closed and 5200 cfm with the doors open. Similarly, for a 5 ft deep hood with an 18 in. front overhang, 1200 cfm was required for three ovens with
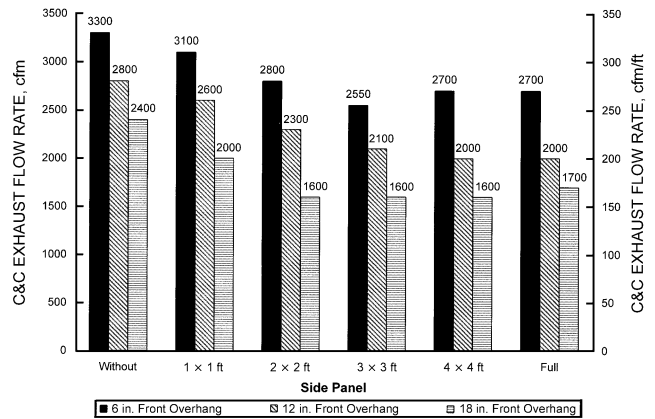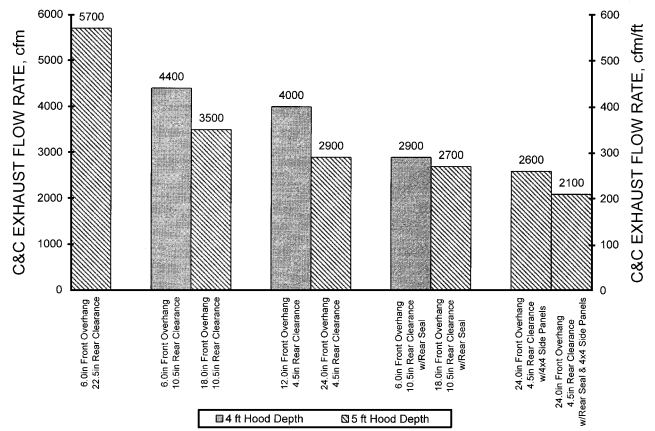
Fig. 9 Exhaust Capture and Containment Rates for a Heavy-Duty Broiler Line under 10 ft Wall Canopy Hood with 4 and 5 ft Hood Depths and Front Various Front Overhangs
(Swierczyna et al. 2005)

the doors closed and 3400 cfm with the doors open. The setup and schlieren views are shown in Figure 10.

The reservoir volume of the hood was increased by changing the hood height from 2 to 3 ft. When the broiler was operated in the left appliance position, the increased hood volume marginally improved capture and containment performance. In contrast, a significant improvement was found for the appliance in the center position. This improvement indicated the plume was well located in the hood, and the increased hood volume may have allowed the plume to roll inside the hood and distribute itself more evenly along the length of the filter bank.

Minimizing hood mounting height had a positive affect on capture and containment performance. In most cases, a direct correlation could be made between the required exhaust rate and hood height for a given appliance line. The typical 6.5 ft mounting height (for a canopy hood) was increased to 7 or 7.5 ft. For the gas broiler installed at the end of the hood, increasing the hood height by 1 ft required a 14% increase in exhaust. However, when the broiler was in the center position, the increased hood height did not compromise capture and containment performance and required a reduced exhaust rate. The dramatic reduction in the exhaust requirement as

(A) NORMAL VIEW

(B) SCHLIEREN VIEW OF SPILLAGE WITH
4 ft DEEP HOOD WITH 6 in.
OF FRONT OVERHANG

(C) SCHLIEREN VIEW DURING CAPTURE AND
CONTAINMENT WITH 5 ft DEEP HOOD WITH
18 in. OF FRONT OVERHANG

Fig. 10 Three Ovens under Wall-Mounted Canopy Hood at Exhaust Rate of 3400 cfm
(Swierczyna et al. 2005)
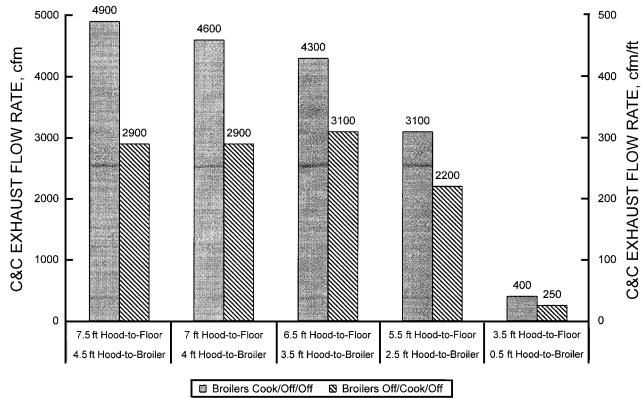
**Fig. 11 Exhaust Capture and Containment Rates for Broiler
under 10 ft Wall Canopy Hood at Various Mounting Heights**
(Swierczyna et al. 2005)

the hood-to-appliance distance was reduced below the 6.5 ft mounting height illustrated the potential for optimizing CKV systems by using close-coupled or proximity-style hoods. This effect is shown in Figure 11.

Design Guidelines. Swierczyna et al. (2005) illustrated the potential for large variations in the airflow requirements for a specified appliance line and hood configuration. Best-practice design considerations that became evident included the following:

- Position heavy-duty appliances (e.g., broilers) in middle of the line.
- Position light-duty appliances (e.g., ovens) on the end of the line.
- Push back appliances (maximize front overhang, minimize rear gap).
- Seal area between rear of appliance and wall.
- Use side panels, end panels, and end walls.
- Installing shelving or ancillary equipment (e.g., salamander) behind or above a range should not negatively affect C&C performance, if other best practices (e.g., maximizing hood overhang) are observed.

Table 4 Exhaust Static Pressure Loss of Type I Hoods for Various Exhaust Airflows*

Type of Grease Removal Device	Hood Static Pressure Loss, in. of water			
	150 to 250 cfm/ft	250 to 350 cfm/ft	350 to 450 cfm/ft	500+ cfm/ft
Baffle filter	0.25 to 0.50	0.50 to 0.75	0.75 to 1.00	1.00 to 1.25
Extractor	0.80 to 1.35	1.30 to 1.70	1.70 to 3.00	2.90 to 4.20
Multistage	0.55 to 1.10	1.10 to 1.70	1.70 to 2.90	2.90 to 4.00

*Values based on 20 in. high filters and 1500 fpm through hood/duct collar.

- Use larger hoods, both deeper and taller.
- Installing hoods at lowest height practical (or allowed by code) to minimize distance from cooking surface to hood improves C&C performance.
- Introduce makeup air at low velocity. Do not locate four-way diffusers near hood, and minimize use of air curtains.

Replacement (Makeup) Air Options. Air exhausted from the kitchen must be replaced. Replacement air can be brought in through traditional methods, such as **ceiling diffusers**, or through systems built as an integral part of the hood. It may also be introduced using low-velocity displacement diffusers or transfer air from other zones. For further information, see the section on Replacement (Makeup) Air Systems.

Static Pressure. Static pressure drop through hoods depends on the type and design of the hood and grease removal devices, size of duct connections, and flow rate. Table 4 provides a general guide for determining static pressure loss depending on the type of grease removal device and exhaust flow rate. Manufacturers' data should be consulted for actual values. Static pressure losses for exhaust ductwork downstream of the hood collar should be calculated for each installation.

Type II Hoods

Type II hoods (Figure 12) can be divided into the following two application categories:

- **Condensate hood.** For applications with high-moisture exhaust, condensate forms on interior surfaces of the hood. The hood is designed to direct the condensate toward a perimeter gutter for

Fig. 12   Type II Hoods

Fig. 13   Particulate Versus Vapor-Phase Emission Percentage per Appliance (Average)
(Gerstler et al. 1998)
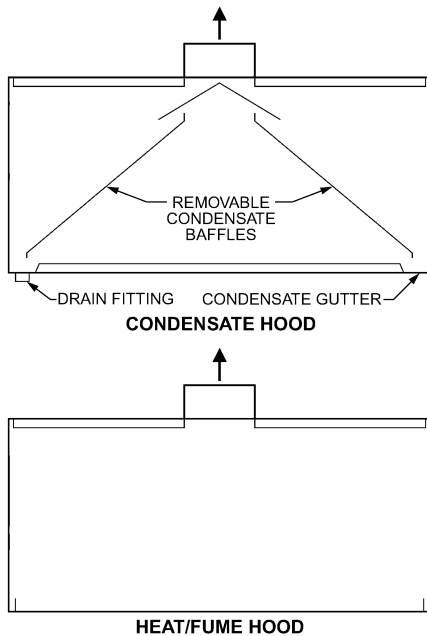
collection and drainage, allowing none to drip onto the appliance below. Flow rates are typically based on 300 to 500 cfm per foot of hood length. Hood material is usually noncorrosive, and filters are usually installed.
- **Heat/fume hood.** For hoods over equipment producing heat and fumes only, flow rates are typically based on 100 to 300 cfm per foot of hood. Filters are usually not installed.

Recirculating Hoods

A recirculating system, previously called a **ductless hood**, consists of a cooking appliance/hood assembly designed to remove grease, smoke, and odor and to return the treated exhaust air directly back into the room. HVAC design must consider that recirculating systems discharge the total amount of heat and moisture generated by the cooking process back into the kitchen space, adding to the cooling load. These hoods typically contain the following components in the exhaust stream: (1) a grease removal device such as a baffle filter, (2) a high-efficiency particulate air (HEPA) filter or an electrostatic precipitator (ESP), (3) some means of odor control such as activated charcoal, and (4) an exhaust fan. NFPA *Standard* 96, Chapter 13, is devoted entirely to recirculating systems and contains specific requirements such as (1) design, including interlocks of all critical components to prevent operation of the cooking appliance if any of the components are not operating; (2) fire extinguishing, including specific nozzle locations; (3) maintenance, including a specific schedule for cleaning filters, ESPs, hoods, and blowers; and (4) inspection and testing of the total operation and interlocks. In addition, NFPA *Standard* 96 requires that all recirculating systems be listed by a testing laboratory. The recognized test standard for a recirculating hood is UL *Standard* 710B. Ductless hoods should not be used over gas-fired or solid-fuel-fired equipment.

Designers should thoroughly review NFPA *Standard* 96 requirements and contact a manufacturer of recirculating hoods to obtain specific information and actual listing test data before incorporating this type of hood into a food service design.

EXHAUST SYSTEMS

Exhaust systems remove effluent produced by appliances and cooking processes to promote fire and health safety, comfort, and aesthetics. Typical exhaust systems simultaneously incorporate fire prevention designs and fire suppression equipment. In most cases, these functions complement each other, but in other cases they may seem to conflict. Designs must balance the functions. For example, fire-actuated dampers may be installed to minimize the spread of fire to ducts, but maintaining an open duct might be better for removing the smoke of an appliance fire from the kitchen.
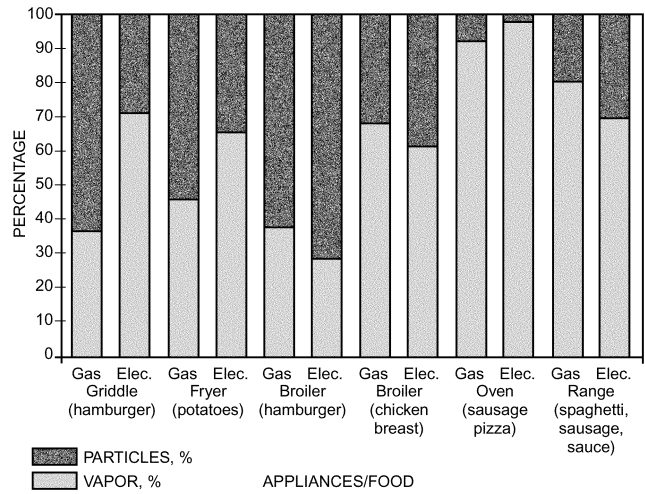
Effluent Control

Effluents generated by cooking include grease in particulate (solid or liquid) and vapor states, smoke particles, and volatile organic compounds (VOCs or low-carbon aromatics, which are significant contributors to odor). Effluent controls in the vast majority of kitchen ventilation systems are limited to removing solid and liquid grease particles by mechanical grease removal devices in the hood. More effective devices reduce grease build-up downstream of the hood, lowering the frequency of duct cleaning and reducing the fire hazard. Higher-efficiency grease removal devices increase the efficiency of smoke and odor control equipment, if present.

The reported grease extraction efficiency of mechanical filtration systems (e.g., baffle filters and slot cartridge filters) may not reflect actual performance. These devices are tested and listed for their ability to limit flame penetration into the plenum and duct, not their grease extraction performance. Research indicates that particulate grease consists of small, aerodynamic particles that are not easily removed by centrifugal impingement, as used in most grease extraction devices (Kuehn et al. 1999). If these particles must be removed, a particulate removal unit is typically added, which removes a large percentage of the grease that escaped the grease removal device in the hood, as well as smoke particles.

ASHRAE Research Project RP-745 (Gerstler et al. 1998) found that a significant proportion of grease effluent may be in vapor form (Figure 13), which is not removed by centrifugal means. Mechanical extraction is not effective in removing vapor.

Grease Extraction

Air quality, fire safety, labor cost, and maintenance costs are important concerns about emissions from a commercial cooking operation. Cooking emissions have also been identified as a major component of smog particulate. This has led to regulation in some major cities, requiring reduction of emissions from specific cooking operations.

In a fire, grease deposits in ductwork act as fuel. Reducing this grease can help prevent a small kitchen fire from becoming a major
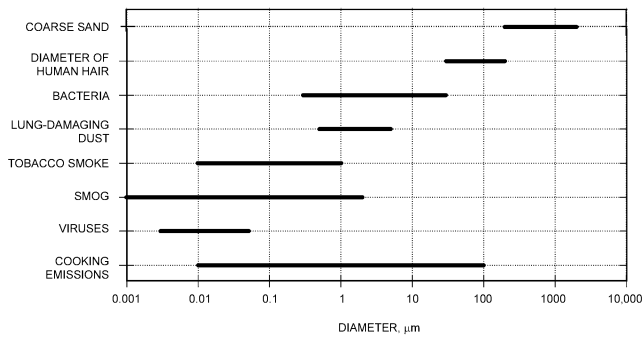
Fig. 14   Size Distribution of Common Particles

Fig. 15   Gas Griddle Mass Emission Versus Particle Size
(Kuehn et al. 1999)

Fig. 16   Gas Charbroiler Mass Emission Versus Particle Size
(Kuehn et al. 1999)

structural fire. In the past, the only control of grease build-up in exhaust ducts was frequent duct cleaning, in which is expensive and disruptive to kitchen operation. It also depends on frequent duct inspections and regular cleaning. Grease build-up on fans, fire nozzles, roofs, and other ventilation equipment can be costly in additional maintenance and replacement costs.

Effluents generated by cooking include grease in particulate and vapor states, smoke particulate, volatile organic compounds (VOCs), and gases (see the section on Effluent Generation). *Grease particulate* is defined as liquid or solid particles that have become suspended in the air; it can range in size from 0.01 to 100 µm. *Grease vapor* refers to gaseous grease that is dispersed into the air when grease is heated. Vapor is at the molecular scale, much smaller than grease particulate. Grease vapor is condensable and may condense into grease particulate in the exhaust airstream when diluted with room-temperature air or when it is exhausted into the cooler outdoor atmosphere.

Particulate down to 10 µm can be filtered out of the airstream. However, vapor and gases cannot be filtered out of an airstream. In theory, this means that most grease particulate could be filtered out of the exhaust, although this is almost never the case. Figure 14 compares the size of particles from kitchen exhaust to common items. In the range of grease particulate size (0.01 to 100 µm), emissions contain different amounts of particulate at different sizes. These quantities at different sizes can be measured and graphed to create a profile of the particulate emissions. Grease particulate larger than 18 to 20 µm is too heavy to remain airborne and drops out of the airstream.

Every combination of cooking process, food product, cooking equipment, and cooking temperature creates a different profile of particles. These profiles change during cooking, as well. The initial drop of French fries into a fryer gives off a short blast of large particles. Cooking a hamburger gives off a continuous stream of particles and vapors, until it is turned: then a large surge of particles, vapors, and gases are given off. If this is on a broiler, the grease that comes off the hamburger tends to burn and emit very small particles.

Variations in the food product itself change the emissions of a cooking process. Hamburger that is 23% fat content produces more grease than a 20% fat content burger. Chicken breast may have a different effluent characteristic than chicken legs or thighs. Even cooking chicken with or without the skin changes the properties of emissions.

Figures 15 and 16 show typical particle emission profiles for a gas griddle and gas charbroiler both cooking hamburgers (Kuehn et al. 1999).

Effluent controls in the majority of today's kitchen ventilation systems are limited to removal of solid and liquid grease particles by mechanical grease removal devices in the hood. These devices cannot remove vapors or gases. Grease removal devices may be tested and listed under UL *Standard* 1046 for their ability to limit flame
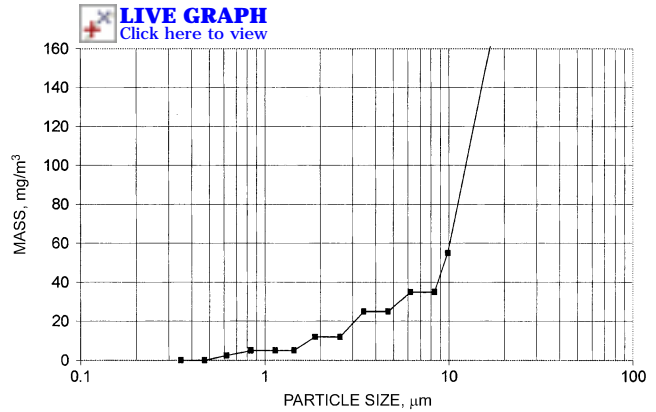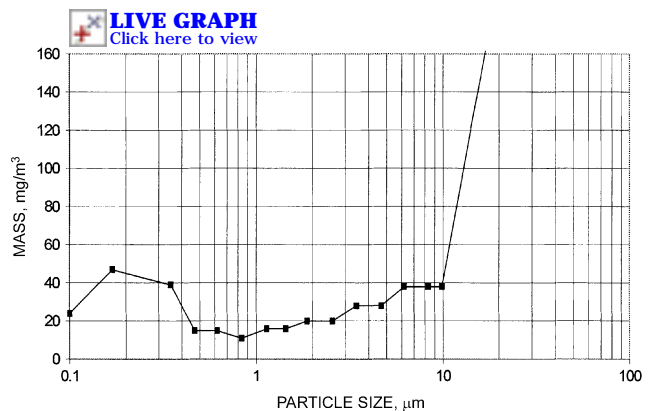
penetration into the plenum and duct, but not their grease extraction performance. The claimed grease extraction efficiency of mechanical filtration systems (e.g., baffle filters and slot cartridge filters) may not reflect performance in the field.

In the past there was no accepted test for evaluating grease removal efficiency for commercial kitchen ventilation in the United States. Those that did exist failed to account for the distribution of particle sizes and vapor.

Filters and grease removal devices can very seldom be given a single meaningful efficiency number, because a filter has different efficiencies for different sizes of particles, flow rates, and phases of particles. A filter that is 90% efficient at removing 10 µm particles may only be 75% efficient at removing 5 µm particles.

ASTM *Standard* F2519-05 can be used to determine fractional filter efficiency for grease particulate. A fractional efficiency curve is a graph that gives a filter's efficiency of over a range of particle sizes. Fractional efficiency curves are created by subjecting a test filter to a controlled distribution of particles and measuring the quantity of particles at each given size before and after the filter. The amount of reduction of particles is used to calculate the efficiency at each given size. The fractional efficiency curve for a typical 20 by 20 in. baffle filter tested at 350 cfm/ft is shown in Figure 17.

Extraction efficiencies must be compared at the same airflow per linear length of filter or hood. This gives a consistent way of comparing performance of extraction devices that may be built very differently, such as hoods with removable extractors and with stationary extractors. This is also consistent with the way exhaust flow rates for hoods are commonly specified. The airflow rate through a hood changes hood efficiency by changing the velocity at which the air travels through a filter.
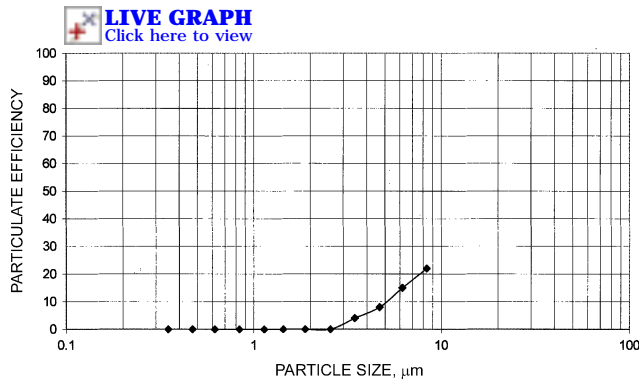
Fig. 17   Baffle Filter Particle Efficiency Versus Particle Size
(Kuehn et al. 1999)
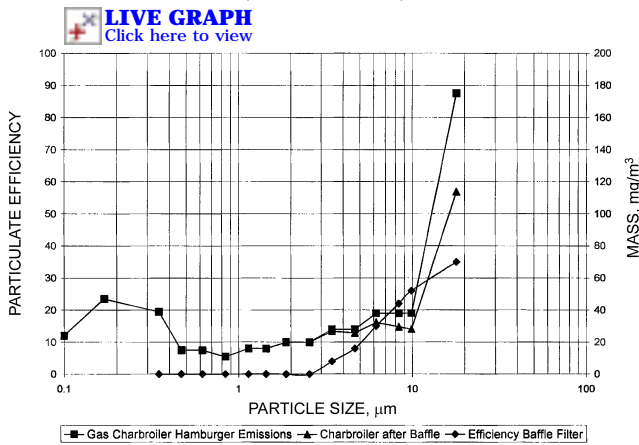
Fig. 18   Particle Efficiency Versus Particle Size
(Kuehn et al. 1999)

To demonstrate what a filter fractional efficiency means with an actual cooking process, the charbroiler emissions curve and the baffle filter efficiency curve have been plotted on one graph in Figure 18. The area under each emission curves is representative of the total particulate emissions for the charbroiler. As can be seen by comparing the graph before and after the baffle filter, there is very little reduction in the amount of grease exhausted to the ductwork. The area under the "charbroiler after baffle" curve represents the amount of grease particulate exhausted into the ductwork.

The graphs and efficiencies shown here are only for particulate grease. There is also a vapor component of the grease that is exhausted, which cannot be removed by filtration. Some of the vapor condenses and is removed as particulate before reaching the filter. Some condenses in the duct and accumulates on the ductwork and fan. However, with elevated temperatures in the exhaust airstream, vapor may pass through and exit to the atmosphere.

Currently, fractional efficiency data exist for very few extraction devices, but soon many filter and hood manufacturers may be able to supply data for their products.

Higher efficiency at a specific particle size is not the only goal. The ultimate goal is to be able to remove the smallest particles and vapor from the airstream. Smaller particles can only be removed by moving the efficiency curve towards the left. The smaller the particle size, the harder it is to remove.

More effective devices reduce grease build-up downstream of the hood, lowering the frequency of duct cleaning and reducing the fire hazard. Higher-efficiency grease removal devices in the hood reduce maintenance of smoke and odor control equipment, if present.

Concerns about air quality also emphasize the need for higher-efficiency grease extraction from the exhaust airstream than can be provided by filters or grease extractors in exhaust hoods. Cleaner exhaust discharge to outside may be required by increasingly stringent air quality regulations or where the exhaust discharge configuration is such that grease, smoke, or odors in discharge would create a nuisance. In some cases, exhaust air is cleaned so that it can be discharged inside (e.g., through recirculating systems). Several systems have been developed to clean the exhaust airstream, each of which presents special fire protection issues.

Where odor control is required in addition to grease removal, activated charcoal, other oxidizing bed filters, or deodorizing agents are used downstream of the grease filters. Because much cooking odor is gaseous and therefore not removed by air filtration, filtration upstream of the charcoal filters must remove virtually all grease in the airstream to prevent grease build-up on the charcoal filters.

The following technologies are available and applied to varying degrees for control of cooking effluent. They are listed by order of use in the exhaust stream after a mechanical filtration device, with particulate control upstream of VOC control. After the description of each technology are qualifications and concerns about its use. There is no consensus test protocol for evaluating these technologies in kitchen applications.

Electrostatic precipitators (ESPs). Particulate removal is by high-voltage ionization, then collection on flat plates.

- Condensed grease can block airflow, especially when mounted outside.
- As the ionizer section becomes dirty, efficiency drops because the effective ionizer surface area is reduced.
- Under heavy loading conditions, the unit may shut down because of voltage drop.

Ultraviolet (UV) destruction. The system uses ultraviolet light to chemically convert the grease into an inert substance and ozone. Construction (not performance) is tested in accordance with UL *Standard* 710C.

- Requires adequate exposure time for chemical reactions.
- Personnel should not look at light generated by high-intensity UV lamps.
- Exhaust fans should operate when UV lights are on because some forms of UV generate ozone.
- UV is more effective on very small particles and vapor.
- The required frequency of duct cleaning is reduced.
- Lamps need to be replaced periodically; as lamps become dirty, efficiency drops.

Water mist, scrubber, and water bath. Passage of the effluent stream through water mechanically entraps particulates and condenses grease vapor.

- High airflow can reduce efficiency of water baths.
- Water baths have high static pressure loss.
- Spray nozzles need much attention; water may need softening to minimize clogging.
- Drains tend to become clogged with grease, and grease traps require more frequent service. Mist and scrubber sections need significant length to maximize exposure time.

Pleated, bag, and HEPA filters. These devices are designed to remove very small particles by mechanical filtration. Some types also have an activated-carbon face coating for odor control.

- Filters become blocked quickly if too much grease enters.
- Static loss builds quickly with extraction, and airflow drops.
- Almost all filters are disposable and very expensive.

Activated-carbon filters. VOC control is through adsorption by fine activated charcoal particles.

- Require a large volume and thick bed to be effective.
- Are heavy and can be difficult to replace.
- Expensive to change and recharge. Many are disposable.
- Ruined quickly if they are grease-coated or subjected to water.

- Some concern that carbon is a source of fuel for a fire.

   Oxidizing pellet bed filters. VOC and odor control is by oxidation of gaseous effluent into solid compounds.

- Require a large volume and long bed to be effective.
- Are heavy to handle and can be difficult to replace.
- Expensive to change.
- Some concern about increased oxygen available in fire.

   Incineration. Particulate, VOC, and odor control is by high-temperature oxidation (burning) into solid compounds.

- Must be at system terminus and clear of combustibles.
- Are expensive to install with adequate clearances.
- Can be difficult to access for service.
- Very expensive to operate.

   Catalytic conversion. A catalytic or assisting material, when exposed to relatively high-temperature air, provides additional heat adequate to decompose (oxidize) most particulates and VOCs.

- Requires high temperature (450°F minimum).
- Expensive to operate due to high temperature requirement.

Duct Systems

   Exhaust ductwork conveys exhaust air from the hood to the outside, along with any grease, smoke, VOCs, and odors that are not extracted from the airstream along the way. This ductwork may also be used to exhaust smoke from a fire. To be effective, ductwork must be greasetight; it must be clear of combustibles, or combustible material must be protected so that it cannot be ignited by a fire in a duct; and ducts must be sized to convey the volume of airflow necessary to remove the effluent.

   Model building codes, such as the IMC (ICC 2006a), and standards, such as NFPA *Standard* 96, set minimum air velocity for exhaust ducts at 500 fpm. Maximum velocities are limited by pressure drop and noise and typically do not exceed 2500 fpm. Until recently, NFPA *Standard* 96 and the IMC set the minimum air velocity through the duct at 1500 fpm. However, based on ASHRAE research (Kuehn 2000) that indicated that there is no basis for specifying 1500 fpm minimum duct velocity for commercial kitchen ventilation, NFPA and IMC requirements were changed to 500 fpm. This allows flexibility for design of variable-speed exhaust systems and retrofitting older systems, though current design practice for new single-speed systems generally continues to use design duct velocity between 1500 and 1800 fpm.

   Ductwork should have no traps that can hold grease, which would be an extra fuel source in the event of a fire, and ducts should pitch toward the hood or an approved reservoir for constant drainage of liquefied grease or condensates. On long duct runs, allowance must be made for possible thermal expansion because of fire, and the slope back to the hood or grease reservoir must conform to local code requirements.

   Single-duct systems carry effluent from a single hood or section of a large hood to a single exhaust termination. In multiple-hood systems, several branch ducts carry effluent from several hoods to a single master duct that has a single termination. See the section on Multiple-Hood Systems for more information.

   Ducts may be round or rectangular. Standards and model codes contain minimum specifications for duct materials and construction, including types and thickness of materials, joining methods, and minimum clearance of 18 in. to combustible materials. Listed factory-built modular grease duct systems are available as an alternative to code-prescribed welded systems. These listed systems typically incorporate stainless steel liners and double-wall, insulated construction, allowing reduced clearances to combustibles and non-welded joint construction.

   When fire-rated enclosures are required for grease ducts, either fired-rated enclosures are built around the duct or the newer listed,
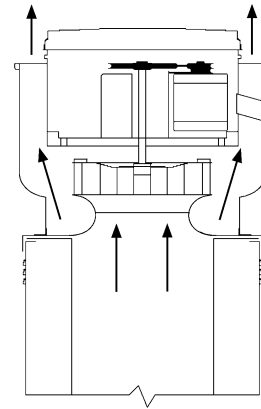
Fig. 19   Power Roof Ventilator (Upblast Fan)
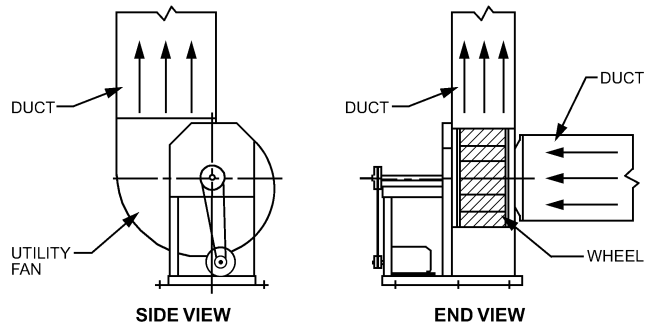
Fig. 20   Centrifugal Fan (Utility Set)

field-applied grease duct enclosures can be used directly on the grease duct, or the newer listed, factory-built, modular grease ducts with insulated construction can be used as an integral fire-rated enclosure. Most of these listed systems allow zero clearance to combustibles and also provide a 2 h fire resistance rating, and can be used in lieu of a fire-rated enclosure required in NFPA *Standard* 96 and IMC (ICC 2006a).

Types of Exhaust Fans

   Exhaust fans for kitchen ventilation must be capable of handling hot, grease-laden air. The fan should be designed to keep the motor out of the airstream and should be effectively cooled to prevent premature failure. To prevent roof damage, the fan should contain and properly drain all grease removed from the airstream.

   The following types of exhaust fans are in common use (all have centrifugal wheels with backward-inclined blades):

- **Power roof ventilator (PRV).** Also known as **upblast** fans, PRVs are designed for mounting at the exhaust stack outlet (Figure 19), and discharge upward or outward from the roof or building. Aluminum upblast fans must be listed for the service in compliance with UL *Standard* 762, and must include a grease drain, grease collection device, and integral hinge kit to permit access for duct cleaning.
- **Centrifugal fan.** Also known as a **utility set**, this is an AMCA Arrangement 10 centrifugal fan, including a field-rotatable blower housing, blower wheel with motors, drives, and often a motor/drive weather cover (Figure 20). These fans are typically constructed of steel and roof-mounted. Where approved, centrifugal fans can be mounted indoors and ducted to discharge outside. The inlet and outlet are at 90° to each other (single width, single inlet), and the outlet can usually be rotated to discharge at different angles around a vertical circle. The lowest part of the fan must
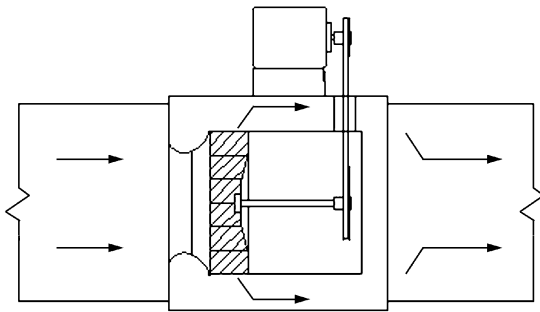
Fig. 21   Tubular Centrifugal (Inline) Fan

drain to an approved container. When listed in accordance with UL *Standard* 762, a grease drain, grease collection device, and blower housing access panel are required.

- **Tubular centrifugal.** These fans, also known as **inline** fans, have the impeller mounted in a cylindrical housing discharging the gas in an axial direction (Figure 21). Where approved, these fans can be located in the duct run inside a building if exterior fan mounting is not practical for wall or roof exhaust. They are always constructed of steel. The gasketed flange mounting must be greasetight yet removable for service. The lowest part of the fan must drain to an approved container. When listed in accordance with UL *Standard* 762 a grease drain, grease collection device, and blower housing access panel are required.

Exhaust Terminations

Rooftop. Rooftop terminations are preferred because discharge can be directed away from the building, the fan is at the end of the system, and the fan is accessible. Common concerns with rooftop terminations are as follows:

- Exhaust system discharge should be arranged to minimize reentry of effluent into any fresh-air intake or other opening to any building. This requires not only separating the exhaust from intakes, but also knowledge of the direction of the prevailing winds. Some codes specify a minimum distance to air intakes.
- In the event of a fire, neither flames, radiant heat, nor dripping grease should be able to ignite the roof or other nearby structures.
- All grease from the fan or duct termination should be collected and drained to a remote closed container to preclude ignition.
- Rainwater should be kept out of the exhaust system, especially out of the grease container. If this is not possible, then the grease container should be designed to separate water from grease and drain the water back onto the roof. Figure 22 shows a rooftop utility set with a stackhead fitting, which directs exhaust away from the roof and minimizes rain penetration. Discharge caps should not be used because they direct exhaust back toward the roof and can become grease-fouled.

Outside Wall. Wall terminations are less common today but are still occasionally used in new construction. The fan may or may not be the terminus of the system, located on the outside of the wall. Common concerns with wall terminations are as follows:

- Discharge from the exhaust system should not be able to enter any fresh-air intake or other opening to any building.
- Adequate clearance to combustibles must be maintained.
- To avoid grease draining down the side of the building, duct sections should pitch back to the hood inside, or a grease drain should be provided to drain grease back into a safe container inside the building.
- Discharge must not be directed downward or toward any pedestrian areas.
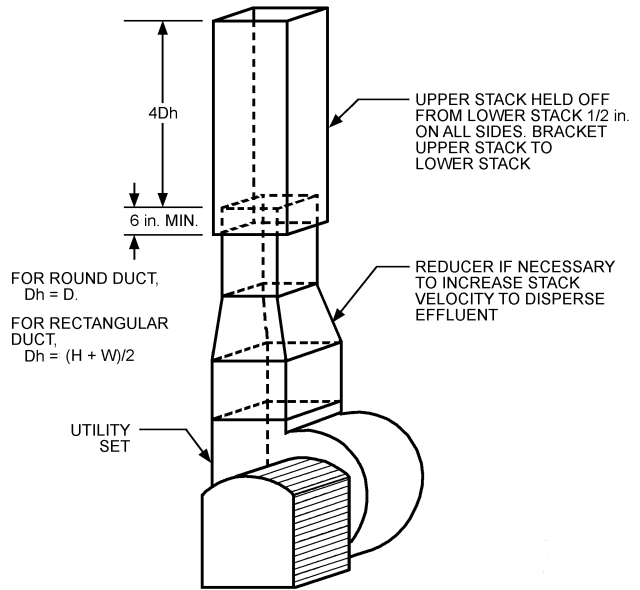
Fig. 22   Rooftop Centrifugal Fan (Utility Set) with Vertical Discharge

- Louvers should be designed to minimize their grease extraction and to prevent staining of the building facade.

Recirculating Hoods. With these units, it is critical to keep components in good working order to maintain optimal performance. Otherwise, excessive grease, heat, and odors will accumulate in the premises.

As with other terminations, containing and removing grease and keeping the discharge as far as possible from combustibles are the main concerns. Some units are fairly portable and could be set in an unsafe location. The operator should be made aware of the importance of safely locating the unit. These units are best for large, unconfined areas with a separate outside exhaust to keep the environment comfortable.

REPLACEMENT (MAKEUP) AIR SYSTEMS

In hood systems, where air exhausted through the hood is discharged to the outside, the volume of air exhausted must be replaced with uncontaminated outside air. Outside air must be introduced into the building through properly designed replacement air systems. Proper replacement air volume and distribution allow the hood exhaust fan to operate as designed and facilitate proper building pressurization, which is required for safe operation of direct-vent gas appliances (such as water heaters), preventing kitchen odors migrating to adjacent building spaces, and maintaining a comfortable building environment. Proper pressurization enhances the building environment by preventing suction of unfiltered and/or unconditioned outside air into the building envelope through doors, windows, or air handlers. IMC (ICC 2006a) requires neutral or negative pressurization in rooms with mechanical exhaust. NFPA *Standard* 96 requires enough replacement air to prevent negative pressures from exceeding 0.02 in. of water, which may still be excessive for proper drafting of some direct vent appliances. To ensure pressure control, IMC also requires electrical interlock between exhaust and replacement air (makeup) sources. This electrical interlock prevents excessive negative or positive pressures created by the exhaust fan or replacement air unit operating independently.

Indoor Air Quality

Traditionally, the primary purpose of replacement air has been to ensure proper operation of the hood. Kitchen thermal comfort and

indoor air quality (IAQ) have been secondary. In some applications, thermal comfort and IAQ can be improved through adequate airflow and proper introduction of replacement air. In many of today's applications, outside air that meets IAQ standards is the most energy-efficient source for kitchen hood replacement air. ASHRAE *Standard* 62.1 requires that 10 cfm outside air per person, based on a maximum occupancy of 70 persons per 1000 ft^2, be brought into the dining area. For cafeterias and fast food dining, the outside air requirement is 9 cfm per person, based on 100 persons per 1000 ft^2. The requirement is 9 cfm per person in nonsmoking bars/cocktail lounges at 100 persons per 1000 ft^2. Kitchens require 14 cfm per person based on 20 persons per 1000 ft^2; however, kitchen requirements for outside air are superseded by the makeup air needs of the exhaust hoods. These requirements may be increased or decreased in certain areas if approved by the authority having jurisdiction. Outside air requirements sometimes affect HVAC system sizing and require another means of introducing outside air. A further requirement of *Standard* 62.1, that outside air be sufficient to provide for an exhaust rate of at least 0.70 cfm per square foot of kitchen space, is generally easily met.

Replacement Air Introduction

Replacement air may be introduced into the building through conventional HVAC apparatus, ventilators (no conditioning), or dedicated kitchen makeup air units and replacement air units. Replacement-air units are specifically designed to supply heated and/or cooled 100% outside air.

Conventional HVAC units used as replacement air sources may have fixed outside air intakes or economizer-controlled outside air dampers. HVAC units with economizers should have a barometric relief damper either in the return ductwork or in the HVAC unit itself. As the amount of outside air is increased, the increase in pressure in the system will open the relief damper, so that the return air volumetric rate is only enough to maintain approximately the amount of design supply air. The supply fan runs at a constant speed and thus moves a constant volume of air. The amount of air required for dedicated replacement air becomes the minimum set point for the economizer damper when the hoods are operating. Fixed outside air intakes must be set to allow the required amount of replacement air. Outside air dampers should be interlocked with hood controls to open to a preset minimum position when the hood system is energized. If the zone controls call for cooling, and outside conditions are within economizer range, the outside damper may be opened to allow greater amounts of outside air. The maximum setting for outside air dampers in unitary HVAC units is typically 25 to 30% of total unit air volume when compressors are running.

Operating in economizer mode should not change air discharge velocities or volumes, because the supply fan runs at a constant speed and thus moves a constant volume of air. However, field experience shows that large increases in air discharge velocities or volumes can occur at diffusers when HVAC units go into economizer mode. This is because the static loss through the fresh-air intake is considerably less than through the return air duct system, and thus a change from return air to fresh air reduces the overall static through the system, resulting in a relative increase in the total system flow. This can create air balance problems that negatively affect hood performance because of interference with capture and containment supply flow patterns at the hoods. A large increase in air velocity or volume from supply diffusers indicates a need for better balance between the fresh air and return air static losses. Some HVAC manufacturers state that a relief fan is required to ensure proper air balance if economizer controls call for outside air greater than 50% during economizer operation mode. A relief fan addresses static losses in the return duct system, thus helping minimize the static difference with the fresh-air intake. Lack of a barometric relief damper, or constrictions in the return ductwork, also may be the source of the problem.

In smaller commercial buildings, including restaurants and strip centers, individual unitary rooftop HVAC equipment is common. This unitary equipment may not be adequate to supply 100% of the replacement air volume. Outside air must be considered in the initial unit selection to obtain desired unit operation and space comfort. The space in which the hood is located should be maintained at a neutral or negative pressure relative to adjacent spaces. Therefore, HVAC economizers are not recommended for equipment supplying air directly to the space in which the hood is located, unless the economizer installation includes equipment and controls to maintain overall system air balance and to prevent excessive air discharge velocities or volumes.

Using enthalpy or temperature control is recommended. These controls cycle HVAC compressor(s), water supply, or heat source off when outside air conditions warrant and open outside air dampers if economizer controls are used. These additional controls provide kitchen comfort while conserving energy and saving money.

Replacement Air Categories

Three categories of replacement air have been defined for design of energy-efficient replacement air systems: supply, makeup, and transfer. IAQ engineers must design outside air systems to meet total building ventilation requirements. Replacement air for kitchen ventilation must integrate into the total building IAQ design. Total kitchen ventilation replacement air may consist of only dedicated makeup air; however, in many energy-efficient designs, outside air required for ventilating the kitchen or adjacent spaces is used as supply or transfer air to augment or even eliminate the need for dedicated makeup air. Typically, replacement air will be a combination of categories from multiple sources. The source of replacement air typically determines its category.

Supply air is outside air introduced through the HVAC or ventilating apparatus, dedicated to the comfort conditioning of the space in which the hood is located. In many cases this may be an ideal source of replacement air as it also provides comfort conditioning for the occupants.

Makeup air is outside air introduced through a system dedicated to provide replacement air specifically for the hood. It is typically delivered directly to or close to the hood. This air may or may not be conditioned. When conditioned, it may be heated only; generally only in extreme environments will it be cooled. When included, makeup air typically receives less conditioning than space supply air. The IMC (ICC 2006a) requires makeup air be conditioned to within 10°F of the kitchen space, except when introducing replacement air does not decrease kitchen comfort (see the section on Energy Considerations for additional information). This can be accomplished with proper distribution design. Typical sources of makeup air conditioning include electric resistance, direct and indirect gas-fired units, evaporative coolers, and water coils for cooling or heating (freeze protection required). Temperature of makeup air introduced varies with distribution system and type of operation.

Transfer air is outside air, introduced through the HVAC or ventilating apparatus, dedicated to comfort conditioning and ventilation requirements of a space adjacent to the hood. The device providing transfer air must be in operation and supplying outside air while the hood is operating. Air must not be transferred from spaces where airborne contaminants such as odors, germs, or dust may be introduced into the food preparation or serving areas. Air may be transferred through wall openings, door louvers, or ceiling grilles connected by duct above the ceiling. Depending on grille and duct pressure drop, a transfer fan(s) may be required to avoid drawing transfer air through lower-pressure-drop openings. When using openings through which food is passed, transfer velocities should not exceed 50 fpm to avoid excessive cooling of the food. Transfer air is an efficient source of replacement air because it performs many functions, including ventilating and/or conditioning the adjacent space, replacing air for the hood, and additional conditioning
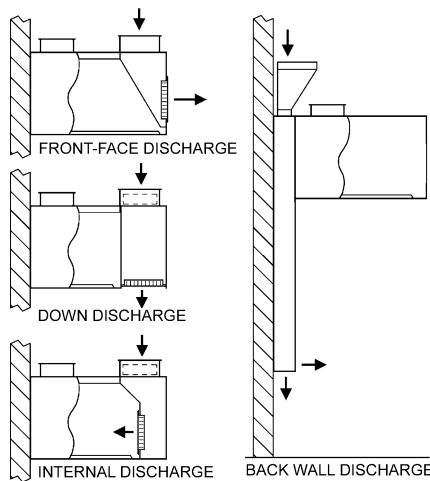
Fig. 23   Internal Methods of Introducing Replacement Air

for the space in which the hood is located. Only the portion of air supplied to the adjacent space that originated as outside air may be transferred for replacement air. The IMC (ICC 2006a) recognizes the use of transfer air as a replacement (makeup) air source. In large buildings such as malls, supermarkets, and schools, adequate transfer air may be available to meet 100% of hood replacement air requirements. Malls and multiple-use-occupancy buildings may specify a minimum amount of transfer air to be taken from their space to keep cooking odors in the kitchen, or they may specify the maximum transfer air available to hold down the cost of conditioning outside air. Code restrictions may prevent the use of corridors as spaces through which transfer air may be routed. Conditions of transfer air are determined by conditioning requirements of the space into which the air is initially supplied.

Air Distribution

The design of a replacement air distribution system can enhance or degrade hood performance. Systems that use a combination of supply, makeup, and transfer air include various components of distribution. Distribution from each source into the vicinity of the hood, must be designed to eliminate high velocities, eddies, swirls, or stray currents that can interrupt the natural rising of the thermal plume from cooking equipment into the hood, thus degrading the performance of the hood. Methods of distribution may include conventional diffusers, compensating hood designs, transfer devices, and simple openings in partitions separating building spaces. Regardless of the method selected, it is important to always deliver replacement air to the hood (1) at proper velocity and (2) uniformly from all directions to which the hood is open. This minimizes excessive cross-currents that could cause spillage. Proper location and/or control of HVAC return grilles is therefore critical. The higher air velocities typically recommended for general ventilation or spot cooling with unconditioned air (75 to 200 fpm at worker) should be avoided around the hood. Hood manufacturers offer a variety of compensating hoods, plenums, and diffusers designed to introduce replacement air effectively.

Compensating Hoods. A common way of distributing replacement air is through compensating systems that are integral with the hood. Figure 23 shows four typical compensating hood configurations. Because actual flows and percentages may vary with hood design, the manufacturer should be consulted about specific applications. The following are typical descriptions.

A recent makeup air study (Brohard et al. 2003) investigated the effects of six strategies on three hood types, and found that each makeup air strategy and specific configuration tested compromised
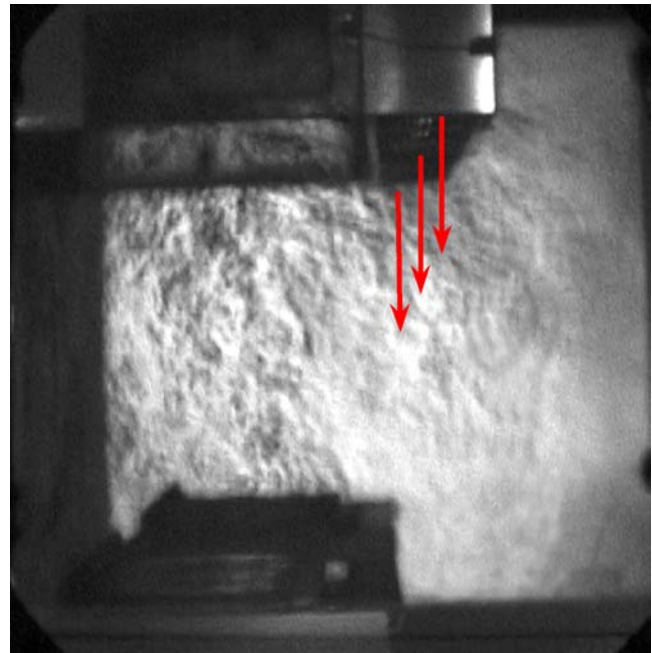
**Fig. 24   Schlieren Image Showing Thermal Plume Being
Pulled Outside Hood by Air Curtain**
(Brohard et al. 2003)

the exhaust hood's ability to completely capture and contain the thermal plume and/or effluents at higher makeup airflow rates (expressed as a percentage of the threshold exhaust rate). Temperature of locally supplied makeup air also affected hood performance, because air density affects the dynamics of air movement around the hood. Generally, hotter makeup air temperatures (e.g., greater than 90°F) affect hood performance more adversely than cooler air (e.g., less than 75°F).

Air Curtain Supply. This method is typically used for spot-cooling the cooking staff to counter the severe radiant heat generated from equipment such as charbroilers. The air must be heated and/or cooled, depending on local climate. Air curtain discharge can be along the length of the hood front only or along all open sides of the hood. When discharge velocity is too low, air tends to enter the hood directly and may have little effect on hood performance. When discharge velocity is too high, air entrains the cooking plume and spills it into the room. Ideal velocity and throw can improve hood performance and redirect the thermal plume toward the filters. Discharge velocities must be carefully selected to avoid discomfort to personnel and cooling of food.

Limit the percentage of makeup air supplied through an air curtain to less than 20% of the hood's exhaust flow. At these low air velocities, an air curtain may enhance capture and containment, depending on design details. However, at higher makeup airflow rates, the air curtain is one of the worst performing makeup air strategies. The negative effect of an air curtain is clearly illustrated in Figure 24 by the schlieren flow visualization recorded during a test of a wall-mounted canopy hood operating over two underfired broilers.

Introducing makeup air through an air curtain is a risky option. An air curtain (by itself or in combination with another pathway) is not recommended, unless velocities are minimized and the designer has access to performance data on the actual air curtain configuration being specified. Typical air curtains are easily adjusted, which could cause cooking effluent to spill into the kitchen by inadvertently creating higher-than-specified discharge velocities.

Back-Wall Supply. A makeup air plenum is installed between the back of the hood and wall. The full-length plenum typically extends down the wall to approximately 6 in. below the cooking surface or
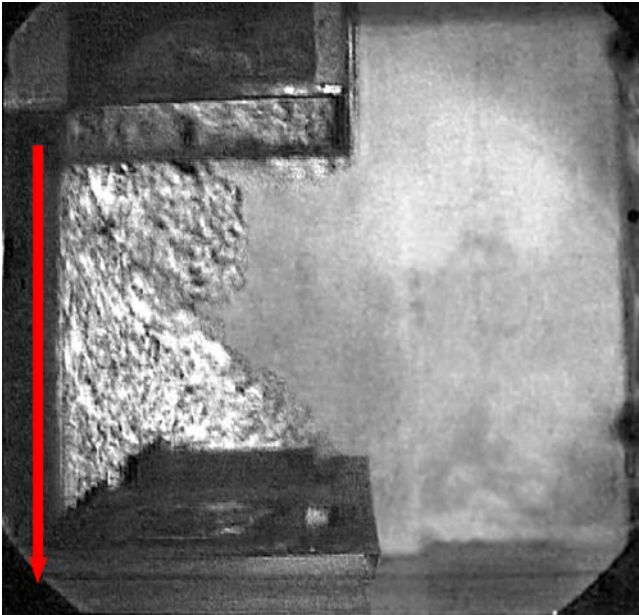
Fig. 25   Schlieren Image Showing Thermal Plume Being Captured with Back-Wall Supply
(Brohard et al. 2003)

Fig. 26   Schlieren Image Showing Thermal Plume Being Pulled Outside Hood by Front Face
(Brohard et al. 2003)

2 to 3 ft above the floor. The depth of the plenum is typically 6 in. Makeup air is discharged behind and below the cooking equipment. The bottom of the plenum is provided with diffusers and may also include a balancing damper. As with front-face discharge, air volume and discharge velocity dictate how far into the space the replacement air will travel. The amount of travel and local climate dictate the amount of heating and/or cooling needed. Support for wall shelves, salamander broilers, or cheesemelters mounted under the hood must be considered. The plenum structure typically does not provide sufficient support for mounting these items.

Back-wall supply can be an effective strategy for introducing makeup air (Figure 25). In most cases, it allows significant amounts of air to be locally supplied without a detrimental effect on hood C&C performance. Local makeup air mostly enters the kitchen space, rather than remaining contained in the cooking zone. This potentially creates an additional heat and moisture load on the kitchen, particularly because most makeup air supplied is mixed with room air before being exhausted.

To help ensure proper performance, the discharge of the back-wall supply should be at least 12 in. below cooking surfaces of appliances, to prevent the relatively high-velocity makeup air from interfering with gas burners and pilot lights. Back-wall plenums with larger discharge areas may provide increased airflow rates as long as discharge velocities remain below maximum thresholds. The quantity of air introduced through the back-wall supply should be no more than 60% of the hood's exhaust flow.

Front-Face Supply. Supplying air through the front face of the hood is a configuration recommended by many hood manufacturers. In theory, air exits the front-face unit horizontally into the kitchen space. However, a front-face discharge with louvers or perforated face can perform poorly, if its design does not consider discharge air velocity and direction. Figure 26 presents a poorly designed perforated face supply, which can negatively affect hood capture performance in the same way as an air-curtain or four-way diffuser. To improve front-face performance, internal baffling and/or a double layer of perforated plates may be used improve the uniformity of airflow. In addition, greater distance between the lower capture edge of the hood and the bottom of the face discharge area may decrease the tendency of the makeup air supply to interfere with hood capture and
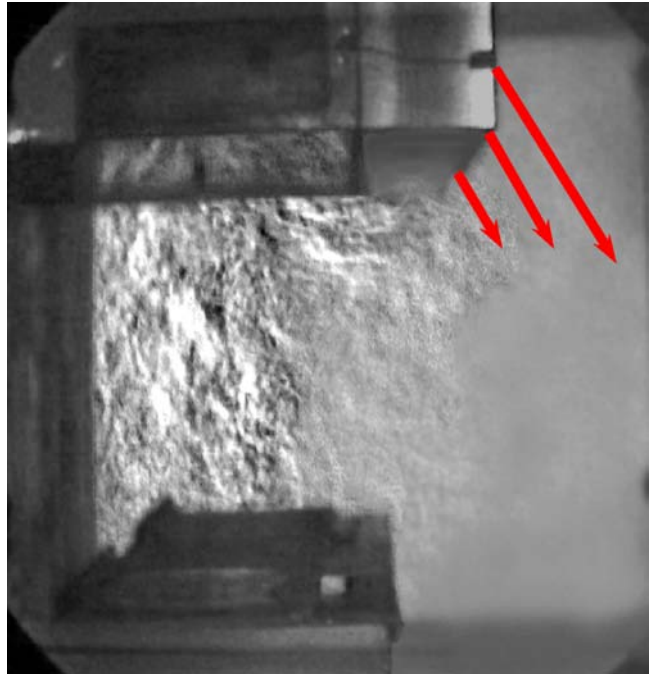
containment. In general, face discharge velocities should not exceed 150 fpm (i.e., makeup air flow rate divided by gross discharge area) and should exit the front face in a horizontal direction.

Internal Makeup Air. Commonly known as **short-circuit**, this method introduces replacement air directly into the exhaust hood cavity. This design has limited application, and the amount of air that can be introduced varies considerably with the type of cooking equipment and exhaust flow rate. As noted previously, thermal currents from cooking equipment create a plume of a certain volume that the hood must remove. The hood must therefore draw at least this volume of air from the kitchen, in addition to any internal makeup. If the net exhaust flow rate (total exhaust less internal replacement air) is less than the plume volume, part of the plume may spill out of the hood. Internal replacement air is typically not conditioned; however, depending on local climate, manufacturer's design, type of cooking equipment, and local codes, conditioning may be required. Some local authorities approve internal discharge hoods, and some do not. For unlisted hoods, IMC (2006a) requires the net quantity of exhaust air to be calculated by subtracting any airflow supplied directly to a hood cavity from the total exhaust flow rate of a hood. Listed hoods are operated in accordance with the terms of the listing. All applicable codes must be consulted to ensure proper criteria are followed.

When short-circuit hoods are operated with excessive internal makeup air, they typically fail to capture and contain the cooking effluent (Figure 27). Additionally, the introduction of untempered makeup air results in uncomfortable kitchen conditions. Independent research recommends not using this compensating hood design; therefore, there is no additional design information in this chapter.

Multiple Discharge. This method may combine internal, perimeter, air curtain, and/or front face. Each may be served by a separate or common plenum. Balancing dampers may be provided for one or both discharge arrangements. These dampers may be used to fine-tune the amount of air discharged through the air curtain or front face. However, this method inherits the installation and maintenance problems of each of the individual types, and the combining
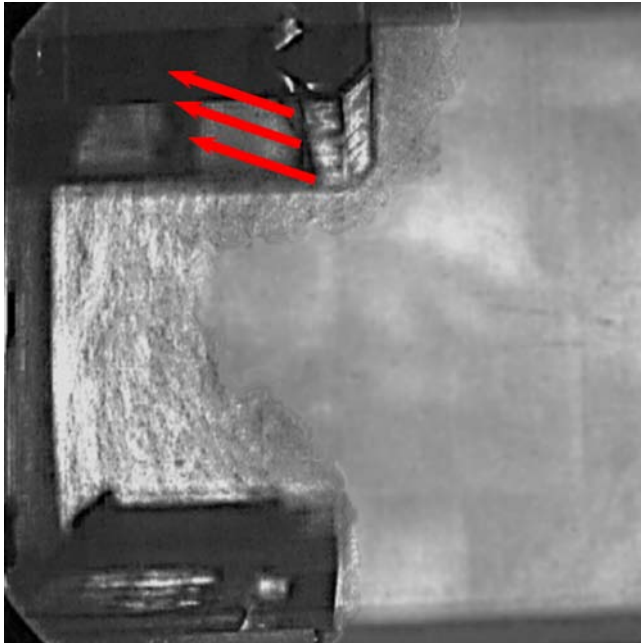
Fig. 27   Schlieren Image Showing Thermal Plume Being Displaced by Short-Circuit Supply, Causing Hood to Spill
(Brohard et al. 2003)

Fig. 29   Schlieren Image Showing Thermal Plume Being Pulled Outside Hood by Air Discharged From Four-Way Diffuser
(Brohard et al. 2003)

Fig. 28   Schlieren Image Shows Effective Plume Capture with Makeup Air Supplied Through 16 in. Wide Perforated Perimeter Supply
(Brohard et al. 2003)

For proper hood performance, discharge velocities should not exceed 150 fpm (i.e., makeup air flow rate divided by gross discharge area) from any section of the diffuser, and the distance to lower edge of the hood should be no less than 18 in., or the system begins to act like an air curtain. An increase in the plenum discharge area lowers the velocity for a given flow of makeup air and reduces the chance of it affecting capture and containment. If the perforated perimeter supply is extended along the sides of the hood as well as the front, the increased area allows proportionally more makeup air to be supplied.

Traditional Registers. There are various ways to distribute replacement air in the vicinity of the hood to avoid cross-currents that degrade hood performance. Nonaspirating diffusers are recommended, especially adjacent to the hood. Typical devices include the following (for more information on diffusers, see Chapter 33 of the 2005 *ASHRAE Handbook—Fundamentals* and Chapter 17 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*).

Louvered Ceiling Diffusers. Air from these aspirating, two-, three-, or four-way diffusers should not be directed toward exhaust hoods, where it might disturb the thermal plume and adversely affect hood performance. The diffuser should be located so that the jet velocity at the lip of the hood does not exceed 75 fpm.

Four-Way Ceiling Diffusers. Four-way diffusers located close to kitchen exhaust hoods (Figure 29) can have a detrimental effect on hood performance, particularly when flow through the diffuser approaches its design limit.

Perforated-plate ceiling diffusers can be used near the hood, and a greater number of ceiling diffusers reduce air velocities for a given supply rate. To help ensure proper hood performance, air from a diffuser near the hood should not be directed toward the hood. They are not recommended within 15 ft of the hood. If ceiling-supplied air must be directed toward a hood, air discharge velocity at the diffuser face should be set at a design value so that the terminal velocity does not exceed 75 fpm at the edge of the hood capture area.

Perforated Diffusers. These nonaspirating, perforated-face diffusers may have internal deflecting louvers, but should not be capable of directing the airflow toward the hood. The diffuser should be

of them tends to compound the associated problems with their design, installation and maintenance.

Perforated Perimeter Supply. Perforated perimeter supply is similar to a front-face supply, but the air is directed downward, as in Figure 28, toward the hood capture area. This may be advantageous under some conditions, because air is directed downward into the hood capture zone.

Fig. 30   Schlieren Image Showing Plume Being Effectively Captured when Makeup Air Is Supplied at Low Velocity From Displacement Diffusers
(Brohard et al. 2003)

located so that the jet velocity at the lip of the hood does not exceed 75 fpm. In some code jurisdictions, when conventional ceiling diffusers are used, only perforated diffusers are allowed in commercial kitchens.

Slot Diffusers. Because the slot opening of these devices is generally small compared to air volume, air velocity is often higher than that which would be obtained with two-, three-, and four-way diffusers. Also, because airflow is mostly downward, the potential for negatively affecting hood performance is quite high if outlets are near the hood. If used with relatively high ceilings, the potential for negative impact is less because the velocity diminishes as air diffuses downward. Slot diffusers are usually nonaspirating.

Displacement Diffusers. These devices, designed to provide low-velocity laminar flow over the diffuser surface, typically supply air from 50 to 70°F in a kitchen, depending on equipment loads. Hotter, stratified air is removed from the ceiling through exhaust ducts or returned to the HVAC system to be conditioned. In contrast with ceiling diffusers, which require complete mixing to be effective, stratification is the desired effect with displacement diffusers.

Displacement ventilation was the baseline for Brohard et al.'s (2003) makeup air study, because it provided a uniform, nearly laminar bulk airflow. This low-velocity bulk airflow is optimal for attaining C&C with the lowest exhaust rate. Therefore, supplying makeup air through displacement diffusers (Figure 30) is an effective strategy for introducing replacement air. Unfortunately, displacement diffusers require floor or wall space, which is usually at a premium in the commercial kitchen. A possible solution may be remote displacement diffusers (built into a corner) to help distribute makeup air into the kitchen when transfer air is not available.

Other Factors That Influence Hood Performance.

Hood Style. Wall-mounted canopy hoods function effectively with a lower exhaust flow rate than single-island hoods. Island canopy hoods are more sensitive to makeup air supply and cross drafts than wall-mounted canopy hoods. Back-shelf/proximity hoods generally exhibit lower capture and containment exhaust rates, and in some cases, perform the same job at one-third of the exhaust rate required by a wall-mounted canopy hood.

Cross Drafts. Cross drafts have a detrimental effect on all hood/appliance combinations. Cross drafts adversely affect island canopy hoods more than wall-mounted canopy hoods. A fan in a kitchen, especially pointing at the cooking area, severely degrades hood performance and may make capture impossible. Cross drafts required at least a 37% increase in exhaust flow rate; in some cases, C&C could not be achieved with a 235% increase in exhaust rate. Cross drafts can result from portable fans, movement in the kitchen, or an unbalanced HVAC system, which may pull air from open drive-through windows or doors.

Side Panels. Side (or end) panels allow a reduced exhaust rate in most cases, because they direct replacement airflow to the front of the hood. Installing side panels improved C&C performance for static conditions an average 10 to 15% and up to 35% for dynamic (cross-draft) conditions. They are a relatively inexpensive way to enhance performance and reduce the total exhaust rate. Partial side panels can provide virtually the same benefit as full panels. One of the greatest benefits of side panels is to mitigate the negative effect of cross drafts.

The primary recommendation from the study was to reduce the impact that locally supplied makeup air may have on hood performance by minimizing makeup air velocity as it is introduced near the hood. This can be accomplished by minimizing the volume of makeup air through any single distribution system, maximizing the area of the diffusers through which the makeup air is supplied, or distributing through multiple pathways. Makeup air supplied through displacement ventilation diffusers, perforated diffusers located in the ceiling as far as possible from the hood, or as transfer air from the dining room generally works well if air velocities approaching the hood are less than 75 fpm. However, makeup air introduced close to an exhaust hood might interfere with the hood's ability to capture and contain. The chances of makeup air affecting hood performance increase as the percentage of the locally supplied makeup air (relative to the total exhaust) is increased. In fact, the 80% rule of thumb for sizing airflow through a makeup air system may be a recipe for trouble.

Design Recommendations. The first step to reducing the makeup air requirement is lowering the design exhaust rate, which can be accomplished by prudent selection and application of UL *Standard* 710 listed hoods. Using side panels on canopy hoods to increase effectiveness, mitigate cross drafts, and reduce heat gain is highly recommended. The next step is to take credit for outside air that must be supplied by the HVAC system to meet code requirements for ventilating the dining room. Depending on the architectural layout, it may be practical to transfer most of this air to the kitchen, improving hood performance and the kitchen environment by introducing conditioned dining room air.

SYSTEM INTEGRATION AND BALANCING

System integration and balancing bring the many ventilation components together to provide the most comfortable, efficient, and economical performance of each component and of the entire system. In commercial kitchen ventilation, the supply air system (typically referred to as the HVAC system) must integrate and balance with the exhaust system. Optimal performance is achieved more by effective use of components through controls and airflow adjustments than by selection or design of the system and components. The following fundamentals for restaurants, and kitchens in particular, should be considered and applied within the constraints of the particular location and its equipment and systems.

Principles

Although there are exceptions, the following are the fundamental principles of integrating and balancing restaurant systems for both comfort control and economical operation:

- In a freestanding restaurant, the overall building should always be slightly positively pressurized compared to the outside to minimize infiltration of untempered air, as well as dirt, dust, and insects, when doors are opened. In multiple-occupancy buildings, a slight negative pressure in the restaurant is desirable to minimize odor migration from the restaurant to other occupancies.
- Every kitchen should always be slightly negative compared to the rooms or areas immediately surrounding it, to (1) better contain unavoidable grease vapors in the kitchen area and limit the extent of cleanup necessary, (2) keep cooking odors in the kitchen area, and (3) prevent the generally hotter and more humid kitchen air from diminishing the comfort level of adjacent spaces, especially dining areas.
- Cross-zoning of airflow should be minimal, especially in temperate seasons, when adjacent zones may be in different modes (e.g., economizer versus air conditioning or heating). Three situations to consider are the following:
  - In transitions from winter to spring and from summer to fall, the kitchen zone could be in economizer, or even mechanical cooling mode, while dining areas are in heating mode. Bringing heated dining-area supply air into a kitchen that is in cooling mode only adds to the cooling load. In some areas, this situation is present every day.
  - When all zones are in the same mode, it is more acceptable, and even more economical, to bring dining-area air into the kitchen. However, the controls to automatically effect this method of operation are more complex and costly.
  - If dedicated kitchen makeup air is heated, thermostatic control of the heating source should ideally be based on kitchen temperature rather than outside temperature. Otherwise, with usual kitchen heat gains and subsequent low balance points for heating and cooling, it is possible that makeup air heating and kitchen mechanical cooling might be operated simultaneously.
- Typically, no drafts should be noticeable, and temperatures should vary no more than 1°F in dining areas and 3°F in kitchen areas. These conditions can be achieved with even distribution and thorough circulation of air in each zone by an adequate number of registers sized to preclude high air velocities. If there are noticeable drafts or temperature differences, customers and restaurant personnel will be distracted and will not enjoy dining or working.

Both design concepts and operating principles for proper integration and balance are involved in achieving desired results under varying conditions. The same principles are important in almost every aspect of restaurant ventilation.

In designing restaurant ventilation, all exhaust is assumed to be in operation at one time, and the design replacement air quantity is a maximum requirement because the heating and cooling equipment are sized for maximum design conditions.

In restaurants with a single large exhaust hood, balancing should be set for this one operation only. In restaurants with multiple exhaust hoods, some may be operated only during heavy business hours or for special menu items. In this case, replacement air must be controlled to maintain minimum building positive pressure and to maintain the kitchen at a negative pressure under all operating conditions. The more variable the exhaust, or the more numerous and smaller the zones involved, the more complex the design, but the overall pressure relationship principles must be maintained to provide optimum comfort, efficiency, and economy.

A different application is a kitchen with one side exposed to a larger building with common or remote dining. Examples are a food court in a mall or a small restaurant in a hospital, airport, or similar building. Positive pressure at the front of the kitchen might cause some cooking grease, vapor, and odors to spread into the common building space, which would be undesirable. In such a case, the kitchen area is held at a negative pressure relative to other common

building areas as well as to its own back room storage or office space.

Air Balancing

Balancing is best performed when the manufacturers of all the HVAC equipment can provide a certified reference method of measuring the airflows, rather than depending on generic measurements of duct flows or other forms of measurement in the field, which can be in error by 20% or more. The equipment manufacturer should be able to develop a reference method of measuring airflow in a portion of the equipment that is dynamically stable in the laboratory as well as in the field. This method should relate directly to airflow by graph or formula.

The general steps for air balancing in restaurants are as follows:

1. Exhaust hoods should be set to their proper flow rates, with supply and exhaust fans on.
2. Next, supply airflow rate, whether part of combined HVAC units or separate replacement air units, should be set to design values through the coils and the design supply flows from each outlet, with approximately correct settings on the outside airflow rate. Then, correct outside and return airflow rates should be set proportionately for each unit, as applicable. These settings should be made with exhaust on, to ensure adequate relief for the outside air.

   Where outside air and return air flows of a particular unit are expected to modulate, there should ideally be similar static losses through both airflow paths to preclude large changes in total supply air from the unit. Such changes, if large enough, could affect the efficiency of heat exchange and could also change airflows within and between zones, thereby upsetting air distribution and balance.
3. Next, outside air should be set with all fans (exhaust and supply) operating. Pressure difference between inside and outside should be checked to see that (1) nonkitchen zones of the building are at a positive pressure compared to outside and (2) kitchen zone pressure is negative compared to the surrounding zones and negative or neutral compared to outside.

   For applications with modulating exhaust, every step of exhaust and replacement should be shut off, one step at a time. Each combination of operation should be rechecked to ensure that design pressures and flows are maintained in each zone and between zones. This requires that the replacement airflow rate compensate automatically with each increment of exhaust. It may require some adjustments in controls or in damper linkage settings to get the correct proportional response.
4. When the preceding steps are complete, the system is properly integrated and balanced. At this time, all fan speeds and damper settings (at all modes of operation) should be permanently marked on the equipment and in the test and balance report. Air balance records of exhaust, supply, return, fresh air, and individual register airflows must also be completed. These records should be kept by the food service facility for future reference.
5. For new facilities, after two or three days in operation (no longer than a week and usually before the facility opens), all belts in the system should be checked and readjusted because new belts wear in quickly and could begin slipping.
6. Once the facility is operational, the performance of the ventilation system should be checked to verify that the design is adequate for actual operation, particularly at maximum cooking and at outside environmental extremes. Any necessary changes should be made, and all the records should be updated to show the changes.

Rechecking the air balance should not be necessary more than once every two years unless basic changes are made in facility operation. If there are any changes, such as adding a new type of cooking

equipment or deleting exhaust connections, the system should be modified accordingly.

Multiple-Hood Systems

Kitchen exhaust systems serving more than a single hood present several design challenges not encountered with single-hood systems. One of the main challenges of multiple-hood exhaust systems is air balancing. Because balancing dampers are not permitted in the exhaust ducts, the system must be balanced by design. Zoning may be desirable for a balanced design and to improve energy conservation. Hood accessories are now available to allow balancing at individual hoods. Additionally, most filters come in varying sizes to allow pressure loss equalization at varying airflows. Some hoods and grease filters have adjustable baffles that allow airflow to be adjusted at the hood. These may be helpful for relatively fine balancing, but the system must provide most of the balancing. System zoning is preferred, because incorrect installation of a multibranch system can lead to complex problems. Adjustable filters should not be used when they can be interchanged between hoods or within the same hood, because an interchange could disrupt the previously achieved balance. Balancing can also be accomplished by changing the number and/or size of filters.

For correct flow through a branch duct in a multiple-hood system, the static pressure loss of the branch must match the static pressure loss of the common duct upstream from the point of connection. Any exhaust points subsequently added or removed must be designed to comply with the minimum velocities required by code and to maintain the balance of the remaining system. In cases such as master kitchen-exhaust systems, which are sometimes used in shopping center food courts, no single group is responsible for the entire design. The base building designer typically lays out ductwork to (or through) each tenant space, and each tenant selects a hood and lays out connecting ductwork. Often the base building designer has incomplete information on tenant exhaust requirements. Therefore, one engineer must be responsible for defining criteria for each tenant's design and for evaluating proposed tenant work to ensure that tenant designs match the system's capacity. The engineer should also evaluate any proposed changes to the system, such as changing tenancy. Rudimentary computer modeling of the exhaust system may be helpful (Elovitz 1992). Given the unpredictability and volatility of tenant requirements, it may not be possible to balance the entire system perfectly. However, without adequate supervision, it is very probable that at least part of the system will be badly out of balance.

For greatest success with multiple-hood exhaust systems, minimize pressure losses in the ducts by keeping velocities low, minimizing sharp transitions, and using hoods with relatively high pressure drops. When pressure loss in the ducts is low compared to the loss through the hood, changes in pressure loss in the ductwork because of field conditions or changes in design airflow will have a smaller effect on total pressure loss and thus on actual airflow.

Minimum code-required air velocity must be maintained in all parts of the exhaust ductwork at all times. If fewer or smaller hoods are installed than the design anticipated, resulting in low velocity in portions of the ductwork, the velocity must be brought up to the minimum. One way is to introduce replacement air, preferably untempered, directly into the exhaust duct where it is required (Figure 31). The bypass duct should connect to the top or sides (at least 2 in. from the bottom) of the exhaust duct to prevent backflow of water or grease through the bypass duct when fans are off. This arrangement is shown in NFPA *Standard* 96 and should be discussed with the authority having jurisdiction.

A fire damper should be provided in the bypass duct, located close to the exhaust duct. Bypass duct construction should be the same as the exhaust duct construction, including enclosure and clearance requirements, for at least several feet beyond the fire damper. Means to adjust the bypass airflow must be provided upstream of the fire

damper. All dampers must be in the clean bypass air duct so they are not exposed to grease-laden exhaust air. The difference in pressure between replacement and exhaust air duct may be great; the balancing device must be able to make a fine airflow adjustment against this pressure difference. It is best to provide two balancing devices in series, such as an orifice plate or blast gate for coarse adjustment followed by an opposed-blade damper for fine adjustment.

Directly measuring air velocities in the exhaust ductwork to assess exhaust system performance may be desirable. Velocity (pitot-tube) traverses may be performed in kitchen exhaust systems, but holes drilled for the pitot tube must be liquidtight to maintain the fire-safe integrity of the ductwork per NFPA *Standard* 96. Holes should never be drilled in the bottom of a duct, where they may collect grease. Velocity traverses should not be performed when cooking is in progress because grease collects on the instrumentation.

Dynamic Volumetric Flow Rate Effects

Design exhaust flow rates for kitchen hoods are determined either by laboratory tests or by building code requirements. In both cases, the intent is to ensure capture and containment under maximum cooking load conditions. The majority of kitchen exhaust systems use fixed-speed fans. Because a fan is a constant-volumetric mover, at any given speed it always moves the same volume of air, regardless of the density of the air, because of temperature, humidity, flue products of combustion, and grease vapor. Thus, for a given motor speed, a kitchen exhaust fan will always move the same volume of air whether during maximum cooking, minimum cooking, with hot appliances at idle, or even with cold appliances. Although the air volume removed by the exhaust fan is constant, the amount of air removed from the kitchen space varies according to cooking appliance operating conditions:

- During full-load cooking, the exhaust system pulls the least amount of air from the kitchen, and requires the least amount of replacement air to keep a balanced system. Air entering the fan inlet consists of the air expanded by the hot cooking surface, effluent generated by the cooked food, entrained kitchen air to ensure capture and containment at the perimeter of the hood, and flue gases when gas-fired equipment is used. This is usually the lightest-density, highest-temperature air removed by the fan.
- During ready-to-cook (idle) conditions (appliances at operating temperature, but no cooking effluent being produced), air being exhausted is a combination of kitchen air (expanded by the hot cooking surface) and entrained kitchen air. Compared to most full-load cooking conditions, the required replacement air volume from the kitchen increases to fulfill the exhaust fan requirement and to keep a balanced system. Air entering the fan inlet is denser than under cooking conditions because the increased volume of kitchen air has a lower temperature than cooking effluent does.
- During cold conditions, air entering the fan inlet is at or near kitchen temperature and humidity conditions. This is the condition with the greatest amount of air leaving the kitchen and
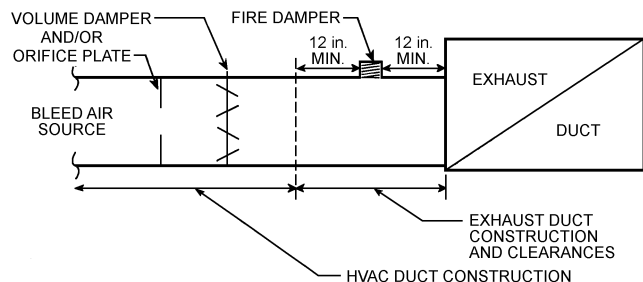
Fig. 31   Method of Introducing Replacement Air Directly into Exhaust Duct

requires the greatest amount of replacement air to keep a balanced system. This is the heaviest-density air of the three appliance operating conditions. In a kitchen, this condition usually occurs for a short while when the exhaust system is first started and before the cooking appliances are heated; it can also occur when the exhaust system is operated to check equipment performance, to assess the air balance and distribution, or to just provide ventilation during a cleaning or renovation project.

Changes in the amount of air volume removed from the kitchen based on appliance operations have implications for (1) setting hood exhaust fan speed in the field, (2) determining the amount of replacement air or transfer air for the kitchen, and (3) air-conditioning and heating loads attributed to makeup air or transfer air.

Appliance temperatures, food and flue products, and exhaust flow rates determine the volume created by the cooking process. The resulting air temperatures vary widely because of overexhausting, close-coupling, hood style, etc. Duct temperatures range from slightly above ambient for large, overexhausted systems to over 200°F for close-coupled minimum-flow systems. The result is a difference in exhaust and replacement air requirements. For instance, two griddles under a backshelf hood could show a 50 cfm difference between exhaust and replacement air, a two-deck oven could show a 200 cfm difference, and two chain charbroilers could show a 500 cfm difference.

The best practice for determining building air balance is to use hot/no cooking (idle) condition flow rates. Most restaurants spend about 70% of their time in this condition. If air balance is determined under cold conditions, the makeup or transfer air will be greater than required during hot/ready-to-cook and cooking operations. The result is a slightly higher pressure than required in the kitchen and may result in air transfer to other parts of the building.

Similarly, the best practice for determining heating and air-conditioning loads from makeup or transfer air is to use hot/no cooking condition flow rates. Using cold/no-cooking conditions will result in a larger design load estimate than required.

ENERGY CONSIDERATIONS

Energy conservation in restaurants depends on the following variables:

Climate. Outside temperature and humidity are key determinants of restaurant HVAC energy use. Because climatic zones vary dramatically in temperature and humidity, kitchen ventilation conservation designs have widely varying economic recovery periods. In new facilities, the designer can select conservation measures suitable for the climatic zone and the HVAC system to maximize the economic benefits.

Restaurant Type. Claar et al. (1985) defined five restaurant types: fast-food, full-service, coffee shop, pizza, and cafeteria. Restaurant associations identify many additional restaurant types, among which energy use varies significantly. As a result, some energy conservation measures work in all restaurants, whereas others may work only in specific types. For simplicity, this discussion classifies restaurants as cafeteria, fast-food, full-menu, and pizza.

Hood Type and Equipment Characteristics. The type of exhaust hood selected depends on such factors as restaurant type, restaurant menu, and food service equipment. Exhaust flow rates are largely determined by the food service equipment and hood style. The effectiveness of conservation measures, whether in a new design or as a retrofit, is also affected by the type of hood and food service equipment.

Energy Conservation Measures

Energy costs in restaurants vary from 2 to 6% of gross sales. The following major energy conservation measures can reduce commercial kitchen ventilation costs.

Custom-Designed Hoods. A typical cooking lineup combines food service equipment with different thermal updraft characteristics and exhaust flow rates depending on cooking load, cooking temperature, product cooked, fuel source, and so forth. Exhaust hoods are sized to handle the worst-case cooking appliance; during idle or off-peak periods, exhaust quantities may be excessive.

Custom-designed hoods for each piece of equipment can reduce exhaust/replacement air quantities and consequently reduce fan sizes, energy use, and energy costs for all types of restaurants. Hood manufacturers recommend exhaust flow rates based on either thermal current charts or empirical tests. To operate at flow rates lower than required by code, custom-designed hoods must be either listed or approved by the local code official.

Dining-Room Air for Kitchen Ventilation. Most fast-food and pizza restaurants do not physically segregate the kitchen from the dining room, so conditioned air moves from the dining area to the kitchen. Dining-room air cools the kitchen and provides replacement air for the kitchen exhaust.

Sometimes full-menu and cafeteria facilities are designed so that minimal replacement air transfers between the dining room and the kitchen; therefore, the majority of the replacement air must be made up by a kitchen makeup air unit.

In restaurants where the kitchen and dining room are physically segregated, ducts between the two areas allow conditioned replacement air to flow to the kitchen. This design can reduce kitchen replacement air requirements and enhance employee comfort, especially if the kitchen is not air conditioned. Of course, the dining room must have replacement air to replace the air transferred to the kitchen. Also, care must be taken to ensure that enough replacement air is introduced into the kitchen to meet the requirements of applicable codes and standards.

Heat Recovery from Exhaust Hood Ventilation Air. High-temperature effluent, often in excess of 400°F, heats replacement air to 100 to 200°F as it travels over the cooking surfaces and areas. It is frequently assumed that this heated exhaust air is suitable for heat recovery; however, smoke and grease in the exhaust air, with time, cover any heat transfer surface. Under these conditions, the heat exchangers require constant maintenance (e.g., automatic washdown) to maintain acceptable heat recovery.

Because heat recovery systems are very expensive, only food service facilities with large amounts of cooking equipment and large cooking loads are good candidates for this equipment. Heat recovery may work in full-menu and cafeteria restaurants and in institutional food service facilities such as prisons and colleges. An exhaust hood equipped with heat recovery is more likely to be cost-effective where the climate is extreme. A mild climate, such as in California, is not conducive to use of this conservation measure. The principal obstacle to heat recovery from kitchen exhaust systems is that heat removal from the exhaust aids condensation of grease vapors on recovery system surfaces in the exhaust stream, resulting in lower heat transfer efficiency and higher maintenance requirements. An additional obstacle is providing enough heat transfer surface area cost-effectively.

Extended Economizer Operation. In most restaurants, mechanical cooling is required to keep the staff and customers cool. By operating in economizer mode, similar cooling can be achieved at less cost because only fans are operated and not compressors. Economizers can be used in lieu of or with mechanical cooling when the outside dry-bulb temperature (and sometimes humidity) is ±10°F lower than the return air condition. Economizer systems may be designed to increase ventilation by 25% or more over normal ventilation, or about 50 to 60% of system supply capacity. For additional savings, economizers can increase outside air to 100%, usually with fan-powered relief. See the on section Replacement Air Sources for design considerations for kitchen applications.

Analysis of energy-use data from monitoring food service facilities indicates that heating/cooling balance points for commercial

kitchens may be significantly lower than the typical 65°F of other commercial buildings. One project that monitored seven diverse restaurants for an extended period (Claar et al. 1985) revealed an average balance point for the group of 53.3°F. Accordingly, though the temperature band for economizer operations in common commercial buildings might be limited to 60 to 75°F, kitchens may benefit from an economizer range starting in the lower 50s, providing for much greater economic application and financial acceptance.

Optimized Heating and Cooling Set Points. IMC (ICC 2006a) requires that makeup air be conditioned to within 10°F of the kitchen space, except when the makeup air is part of the air-conditioning system and does not adversely affect comfort conditions in the occupied space. The exception is important because it allows the design to be optimized to take advantage of the typically lower heating/cooling balance points of commercial kitchens. Accordingly, it is essential that the heating set point of dedicated makeup units not be set higher than the forecasted heating/cooling balance point to avoid simultaneous operation of makeup heating and HVAC cooling. Designers should set the makeup unit heating exit temperature lower than the lowest temperature at which cooling will be activated.

Reduced Exhaust and Replacement (Makeup) Airflow Rates. Tempering outside replacement air can account for a large part of a food service facility's heating and cooling costs. By reducing exhaust flow rates (and the corresponding replacement air quantity) when no product is being cooked, energy cost can be significantly reduced. Field evaluations by one large restaurant chain suggest that cooking appliances may be at zero load for 75% or more of an average business day (Spata and Turgeon 1995). When no smoke or grease-laden vapors are being produced, NFPA *Standard* 96 allows reduction of exhaust quantities. The only restriction on the reduced exhaust quantity is that it be "sufficient to capture and remove flue gases and residual vapors."

Historically, however, it has been difficult to reduce exhaust flow rates in a retrofit because of the minimum duct velocity restriction. ASHRAE research (Kuehn 2000) shows that, for design duct velocities below the traditional 1500 fpm threshold, grease deposition was not increased. NFPA *Standard* 96 had historically required a minimum duct velocity of 1500 fpm. The common belief was that if the duct velocity were lowered, a higher percentage of grease would accumulate on the ductwork, which would then require more frequent duct cleaning. However, no data or research could be identified to support this assumption. Therefore, ASHRAE Research Project RP-1033 (Kuehn 2000) was undertaken to determine the true effect of duct velocity on grease deposition.

The project analyzed grease deposition as a function of mean duct velocity, using octanoic acid (commonly found in cooking oils and other foods). This project confirmed that grease deposition on ductwork is a function of three components: turbulence, thermophoresis, and gravitational settling. Turbulence is a function of grease particle velocity, particle size, and interactions of exhaust air with duct walls. Thermophoresis is caused by a temperature difference between the exhaust airstream and the duct walls and, in simple terms, accounts for grease condensing on the duct walls. Gravitational settling accounts for the effect of gravity. In vertical ductwork that is insulated or relatively adiabatic, turbulence is the determining factor for whether grease accumulates on ductwork walls, and can be accounted for using the deposition velocity. RP-1033 found that if duct velocity is decreased in an insulated duct, grease deposition on all sides of the duct is decreased. Figure 32 shows the deposition velocity of grease particles on the side of the ductwork at different exhaust airflows.

Another significant finding in the study was that, if there is a large temperature gradient between exhaust air inside the duct and the external duct wall, the rate of grease deposition increases significantly. Therefore, duct insulation should be considered where there are large temperature variations.

These results led to NFPA *Standard* 96 changing its minimum duct velocity requirements from 1500 fpm to 500 fpm. This requirement has also been incorporated by the IMC (ICC 2006).

The primary implication for this change is to reduce restaurant energy consumption by reducing exhaust airflow during idle periods, while maintaining necessary capture and containment. This reduces exhaust fan energy consumption and replacement air energy requirements by changing exhaust airflows during cooking and idle periods of the day. Previously, if a restaurant remodeled their cooking operation and reduced the exhaust airflows, the owner had to install smaller-diameter ductwork to meet the 1500 fpm requirement, which was costly. Now, if a system is designed for heavy-duty equipment, and instead lighter-duty equipment is installed, exhaust airflows can be reduced without the expense of modifying ductwork.

From a design perspective, it is recommended that most kitchens be designed for an in-duct velocity between 1500 and 1800 fpm. This allows for reducing the airflows to 500 fpm if needed in the future.

FIRE PROTECTION

The combination of flammable grease and particulates carried by kitchen ventilation systems and the potential of cooking equipment to be an ignition source creates a higher hazard level than normally found in HVAC systems. Design of an exhaust system serving cooking equipment that may produce grease-laden vapors must provide, at a minimum, a reasonable level of protection for the safety of building occupants and fire fighters. The design can be enhanced to provide extra protection for property.

Replacement air systems, air-conditioning systems serving a kitchen, and exhaust systems serving only cooking equipment that does not produce grease-laden vapor have no specific fire protection requirements beyond those applicable to similar systems not located in kitchens. However, an exhaust system serving any grease-producing cooking equipment must be considered a grease exhaust system even if it also serves non-grease-producing equipment.

Fire protection starts with proper operation and maintenance of the cooking equipment and the exhaust system. After that, the two primary aspects of fire protection in a grease exhaust system are (1) to extinguish a fire quickly once it has started and (2) to prevent the spread of fire from or to the grease exhaust system.

Fire Suppression

NFPA *Standard* 96 requires that exhaust systems serving grease-producing equipment must include a fire-extinguishing system, which must protect cooking surfaces, hood interior, hood filters or grease extractors, ducts, and any other grease-removal devices in the system. The most common fire-extinguishing systems are wet chemical and water spray systems.

Operation. Actuation of any fire-extinguishing system should not depend on normal building electricity. If actuation relies on electricity, it should be supplied with standby power.

Any extinguishing system must automatically shut off all supplies of fuel and heat to all equipment protected by that system. Any gas appliance not requiring protection but located under the same ventilating equipment must also be shut off. On operation of a wet chemical or water fire-extinguishing system, all electrical sources located under the ventilating equipment, if subject to exposure to discharge from the fire-extinguishing system, must be shut off. If the hood is in a building with a fire alarm system, actuation of the hood extinguishing system should send a signal to the fire alarm.

Dry and Wet Chemical Systems. Wet chemical fire-extinguishing systems are the most common in new construction for protecting hoods and exhaust systems. Dry chemical systems were popular; however, most manufacturers have removed them

(A) MMAD = 4.3 μm, ISOTHERMAL CONDITIONS

(B) MMAD = 1.6 μm, ISOTHERMAL CONDITIONS

(C) MMAD = 1.6 μm, EXHAUST AIR TEMPERATURE = 120°F

(D) MMAD = 1.6 μm, EXHAUST AIR TEMPERATURE = 150°F
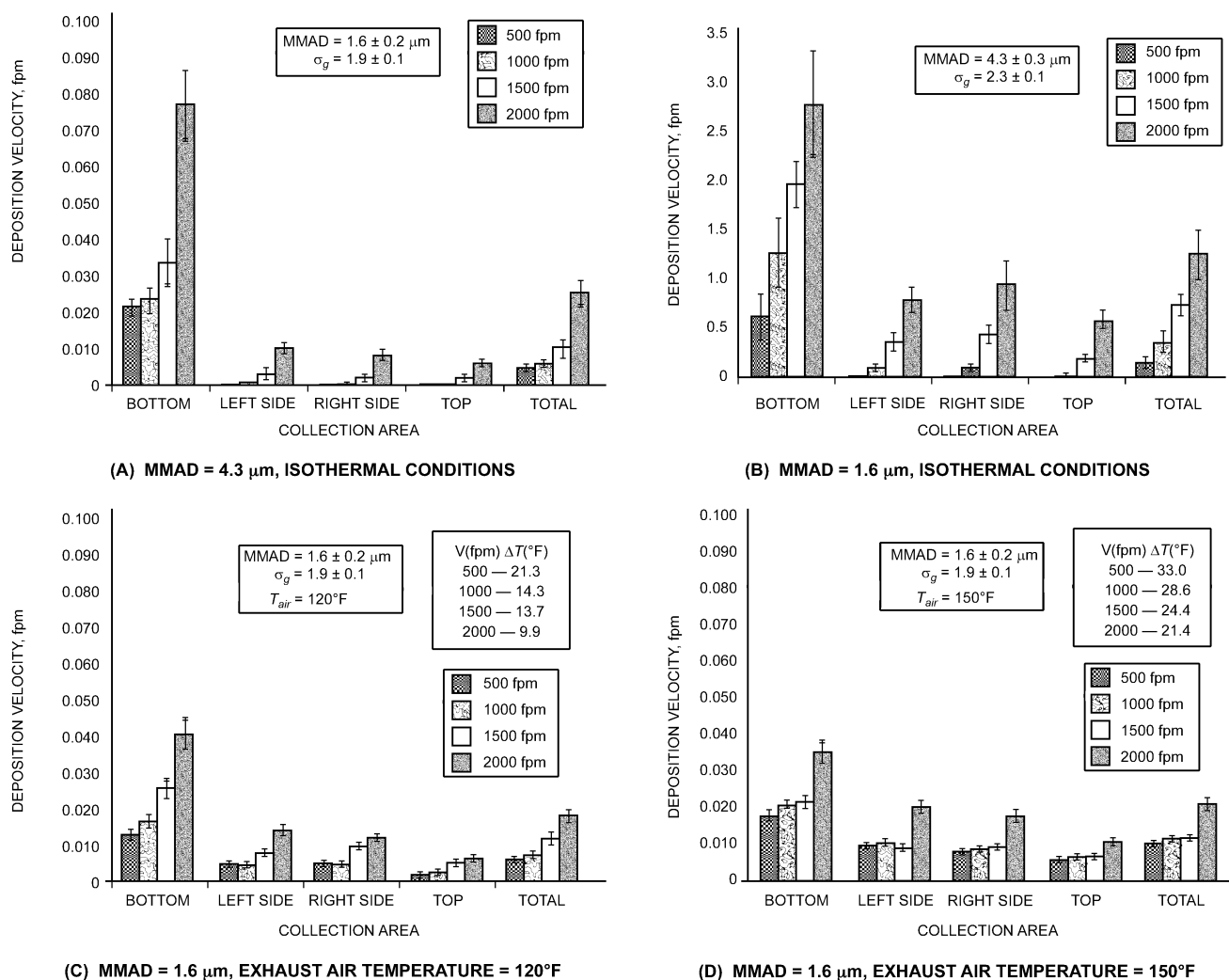
Fig. 32 Deposition Velocity of Polydispersed Particles on Internal Surfaces of Horizontal Square Exhaust Duct Versus Mean Exhaust Velocity
(Kuehn 2000; MMAD = mass mean aerodynamic diameter)

from the market because they have not passed UL *Standard* 300. Dry chemical systems are covered in NFPA *Standard* 17, and wet chemical systems are covered in NFPA *Standard* 17A. Both standards provide detailed application information. Systems are tested for their ability to extinguish fires in cooking operations in accordance with UL *Standard* 300. To date, only wet chemical systems are listed to UL *Standard* 300.

Both dry and wet chemicals extinguish a fire by reacting with fats and grease to **saponify**, or form a soapy foam layer that prevents oxygen from reaching the hot surface. This suppresses the fire and prevents reignition. Saponification is particularly important with deep fat fryers, where the frying medium may be hotter than its autoignition temperature for some time after the fire is extinguished. If the foam layer disappears or is disturbed before the frying medium has cooled below its autoignition temperature, it can reignite.

Frying media commonly used today have autoignition points of about 685 to 710°F when new. Contamination through normal use lowers the autoignition point. The chemical agent that extinguishes the fire also contaminates the frying medium, which can further reduce the autoignition point by 50 to 60°F. One advantage of wet chemical systems over dry chemical systems is that the wet chemical provides extra cooling to the frying medium, so that it falls below the autoignition point more quickly.

For a chemical system protecting the entire exhaust system, fire-extinguishing nozzles are located over the cooking equipment being protected, in the hood to protect grease-removal devices and the hood plenum, and at the duct collar (downstream from any fire dampers) to protect ductwork. The duct nozzle is rated to protect an unlimited length of ductwork, so additional nozzles are not required further downstream in the ductwork. Fire detection is required at the entrance to each duct (or ducts, in hoods with multiple duct takeoffs) and over each piece of cooking equipment that requires protection. The detector at the duct entrance may also cover the piece of cooking equipment directly below it.

Chemical fire-extinguishing systems are available as listed, pre-engineered (packaged) systems. Chemical systems typically consist of one or more tanks of chemical agent (dry or wet), a propellant gas, piping to the suppression nozzles, fire detectors, and auxiliary equipment. The fire detectors are typically fusible links that melt at a set temperature associated with a fire, although electronic devices are also available. Auxiliary equipment may include manual pull stations, gas shutoff valves (spring-loaded or solenoid-actuated), and auxiliary electric contacts.

Actuation of dry and wet chemical suppression systems is typically completely mechanical, requiring no electric power. Fire detectors are typically interconnected with the system actuator by

steel cable in tension, so that melting of any fusible links releases the tension on the steel cable, causing the actuator to release the propellant and suppressant. The total length of the steel cable and the number of pulley elbows permitted are limited. A manual pull station is typically connected to the system actuator by steel cable. If a mechanical gas valve is used, it is also connected to the system actuator by steel cable. System actuation also switches auxiliary dry electrical contacts, which can be used to shut off electrical cooking equipment, operate an electric gas valve, shut off a replacement air fan, and/or send an alarm signal to the building fire alarm system.

Manual pull stations are generally required to be at least 10 ft from the cooking appliance and in a path of egress. Some authorities may prefer that the pull station be installed closer to the cooking equipment, for faster response; however, if it is too close, it may not be possible to approach it once a fire has started. Refer to the applicable code requirements for each jurisdiction to determine specific requirements for location and mounting heights of pull stations.

Water Systems. Water can be used for protecting cooking appliances, hoods, and grease exhaust systems. Standard fire sprinklers may be used throughout the system, except over deep-fat fryers, where special automatic spray nozzles specifically listed for the application must be used. These nozzles must be aimed properly and supplied with the correct water pressure. Many hood manufacturers market a pre-engineered water spray system that typically includes a cabinet containing the necessary plumbing and electrical components to monitor the system and initiate fuel shutoff and building alarms.

Application of standard fire sprinklers for protection of cooking appliances, hoods, and grease exhaust systems is covered by NFPA *Standard* 13. NFPA *Standards* 25 and 96 covers maintenance of sprinkler systems serving an exhaust system. The sprinklers must connect to a wet-pipe building sprinkler system installed in compliance with NFPA *Standard* 13.

Water systems that spray a fine mist can be used to protect cooking equipment. Nozzles protecting deep fat fryers must be specifically listed for this use. The water spray suppresses the fire in two ways: the mist spray absorbs heat from the fire, and then becomes steam, which displaces air and suffocates the fire.

Although standard sprinklers may be used to protect cooking equipment other than deep-fat fryers, care must be taken to ensure that sprinklers are properly selected for a fine mist discharge; if pressure is too high or the spray too narrow, the water spray could push flames off the cooking equipment.

One advantage of a sprinkler system is that it has virtually unlimited capacity, whereas chemical systems have limited chemical supplies. This can be an advantage in suppressing a fire, but all the water must be safely removed from the space. Where sprinklers are used in ducts, the ductwork should be pitched to drain safely. NFPA *Standard* 13 requires that sprinklers used to protect ducts be installed every 10 ft on center in horizontal ducts, at the top of every vertical riser, and in the middle of any vertical offset. Any sprinklers exposed to freezing temperatures must be protected.

Hoods that use water either for periodic cleaning (water-wash) or for grease removal (cold water mist) can use this feature in conjunction with the fire-extinguishing system to protect the hood, grease-removal device, and/or ducts in the event of a fire. The water supply for these systems may be from the kitchen water supply if flow and pressure requirements are met. These hoods can also act as a fire stop because of their multipass configuration and the fact that the grease extractors are not removable.

Combination Systems. Different system types may protect different parts of the grease exhaust system, as long as the entire system is protected. Examples include (1) an approved water-wash or water mist system to protect the hood in combination with a dry or wet chemical system to protect ducts and the cooking surface or (2) a chemical system in the hood backed up by water sprinklers in

the ductwork. Combination systems are more common in multiple-hood systems, where a separate extinguishing system may be used to protect a common duct. If combination systems will discharge their suppressing agents together in the same place, the agents must be compatible.

Multiple-Hood Systems. All hoods connected to a multiple-hood exhaust system must be on the same floor of the building to prevent the spread of fire through the duct from floor to floor. Preferably, there should be no walls requiring greater than a 1 h fire resistance rating between hoods.

The multiple-hood exhaust system must be designed to (1) prevent a fire in one hood or in the duct from spreading through the ducts to another hood and (2) protect against a fire starting in the common ductwork. Of course, the first line of protection for the ducts is keeping it clean. Especially in a multiple-tenant system, a single entity must assume responsibility for cleaning the common ductwork frequently.

Each hood must have its own fire-extinguishing system to protect the hood and cooking surface. A single system could serve more than one hood, but in the event of fire under one hood, the system would discharge its suppressant under all hoods served, resulting in unnecessary cleanup expense and inconvenience. A water-mist system could serve multiple hoods if sprinkler heads were allowed to operate independently.

Because of the possibility of a fire spreading through ducts from one hood to another, the common ductwork must have its own fire protection system. The appendices of NFPA *Standards* 17 and 17A present detailed examples of how common ducts can be protected either by one system or by a combination of separate systems serving individual hoods. Different types of fire-extinguishing systems may be used to protect different portions of the exhaust system; however, in any case where two different types of system can discharge into the common duct at the same time, the agents must be compatible.

As always, actuation of the fire-extinguishing system protecting any hood must shut off fuel or power to all cooking equipment under that hood. When a common duct, or portion thereof, is protected by a chemical fire-extinguishing system that activates from a fire in a single hood, NFPA *Standards* 17 and 17A require shutoff of fuel or power to the cooking equipment under every hood served by that common duct, or portion of it protected by the activated system, even if there was no fire in the other hoods served by that duct.

From an operational standpoint, it is usually most sensible to provide one or more fire-extinguishing systems to detect and protect against fire in common ducts and a separate system to protect each hood and its connecting ducts. This (1) prevents a fire in the common duct from causing discharge of fire suppressant under an unaffected hood and (2) allows unaffected hoods to continue operation in the event of a fire under one hood unless the fire spreads to the common duct.

Preventing Fire Spread

The exhaust system must be designed and installed both to prevent a fire starting in the grease exhaust system from damaging the building or spreading to other building areas and to prevent a fire in one building area from spreading to other parts of the building via the grease exhaust system. This protection has two main aspects: (1) maintaining clearance from the duct to other portions of the building and (2) enclosing the duct in a fire-resistance-rated enclosure. Both aspects are sometimes addressed by a single action.

Clearance to Combustibles. A grease exhaust duct fire can generate gas temperatures of 2000°F or greater in the duct. In such a grease fire, heat radiating from the hot duct surface can ignite combustible materials near the duct. Most codes require a minimum clearance of 18 in. from the grease exhaust duct to any combustible material. However, even 18 in. may not be sufficient clearance to

prevent ignition of combustibles in the case of a major grease fire, especially in larger ducts.

Several methods to protect combustible materials from the radiant heat of a grease duct fire and permit reduced clearance to combustibles are described in NFPA *Standard* 96. Previous editions required that these protections be applied to the combustible material rather than to the duct, on the theory that if the duct is covered with an insulating material, the duct itself will become hotter than it would if it were free to radiate its heat to the surroundings. The hotter temperatures could result in structural damage to the duct. NFPA *Standard* 96 now allows materials to be applied to the actual duct. However, because this edition may not have been accepted by some jurisdictions, the authority having jurisdiction should be consulted before clearances to combustible materials are reduced.

Listed grease ducts, typically double-wall ducts with or without insulation between the walls, may be installed with reduced clearance to combustibles in accordance with manufacturers' installation instructions, which should include specific information regarding the listing. Listed grease ducts are tested under UL *Standard* 1978.

NFPA *Standard* 96 also requires a minimum clearance of 3 in. to "limited combustible" materials (e.g., gypsum wallboard on metal studs). At present, none of the standards and model codes requires any clearance to noncombustible materials except for enclosures.

Enclosures. Normally, when a duct penetrates a fire-resistance-rated wall or floor, a fire damper is used to maintain the integrity of the wall or floor. Because fire dampers may not be installed in a grease exhaust duct unless specifically approved for such use, there must be an alternative means of maintaining the integrity of rated walls or floors. Therefore, grease exhaust ducts that penetrate a fire-resistance-rated wall or floor-ceiling assembly must be continuously enclosed in a fire-rated enclosure from the point the duct penetrates the first fire barrier until the duct leaves the building. Listed grease ducts are also subject to these enclosure requirements. The requirements are similar to those for a vertical shaft (typically 1 h rating if the shaft penetrates fewer than three floors, 2 h rating if it penetrates three or more floors), except that the shaft can be both vertical and horizontal. In essence, the enclosure extends the room containing the hood through all the other compartments of the building without creating any unprotected openings to those compartments.

Where a duct is enclosed in a rated enclosure, whether vertical or horizontal, clearance must be maintained between the duct and the shaft. NFPA *Standard* 96 and IMC (ICC 2006a) require minimum 6 in. clearance and that the shaft be vented to the outside. IMC requires that each exhaust duct have its own dedicated enclosure.

Some listed grease ducts are designed and tested for use without shaft enclosure. Listed grease ducts of this type typically incorporate integral fire protection, which serves the same function as the shaft enclosure. These products are tested and listed in accordance with UL *Standard* 2221. They must be installed in strict compliance with the manufacturer's installation instruction.

Some available materials are listed to serve as a fire-resistance-rated enclosure for a grease duct when used to cover a duct directly with minimal clear space between the duct and the material. These materials are tested and listed in accordance with ASTM *Standard* E2336 or the International Code Council (ICC 2004). These listed materials must be applied in strict compliance with the manufacturer's installation instructions, which may limit the size of duct to be covered and specify required clearances for duct expansion and other installation details. When a duct is directly covered with an insulating material, there is a greater chance of structural damage to the duct from the heat of a severe fire. Structural integrity of exhaust ducts should be assessed after any serious duct fire.

Insulation materials that have not been specifically tested and approved for use as fire protection for grease exhaust ducts should not be used in lieu of rated enclosures or to reduce clearance to combustibles. Even insulation approved for other fire-protection

applications, such as to protect structural steel, may not be appropriate for grease exhaust ducts because of the high temperatures that may be encountered in a grease fire.

The IMC (ICC 2006a) requires that listed grease ducts installed without shaft enclosure be tested and listed in accordance with UL *Standard* 2221. Likewise, grease duct enclosure materials must be tested and listed in accordance with ASTM *Standard* E2336.

Exhaust and Supply Fire-Actuated Dampers. Because of the risk that the damper may become coated with grease and become a source of fuel in a fire, balancing and fire-actuated dampers are not permitted at any point in a grease exhaust system except where specifically listed for each use or required as part of a listed device or system. Typically, fire dampers are found only at the hood collar and only if provided by the manufacturer as part of a listed hood.

Opinions differ regarding whether any fire-actuated dampers should be provided in the exhaust hood. On one hand, a fire-actuated damper at the exhaust collar may prevent a fire under the hood from spreading to the exhaust duct. However, like anything in the exhaust airstream, the fire-actuated damper and linkage may become coated with grease if not properly maintained, which may impede damper operation. On the other hand, without fire-actuated dampers, the exhaust fan will draw smoke and fire away from the hood. Although this cannot be expected to remove all smoke from the kitchen during of a fire, it can help to contain smoke in the kitchen and minimize migration of smoke to other areas of the building.

A fire-actuated damper will generally close only in the event of a severe fire; most kitchen fires are extinguished before enough heat is released to trigger the fire-actuated damper. Thus the hood fire-actuated damper remains open during relatively small fires, allowing the hood to remove smoke, but can close in the event of a severe fire, helping to contain the fire in the kitchen area.

Fan Operations. If it is over 2000 cfm, the replacement air supply to the kitchen is generally required to be shut down during fire to avoid feeding air to the fire. However, if the exhaust system is intended to operate during a fire to remove smoke from the kitchen (as opposed to just containing it in the kitchen), the replacement air system must operate as well. If the hood has an integral replacement air plenum, a fire-actuated damper must be installed in the replacement air collar to prevent a fire in the hood from entering the replacement air ductwork. NFPA *Standard* 96 details the instances where fire-actuated dampers are required in a hood replacement air assembly.

Regardless of whether fire-actuated dampers are installed in the exhaust system, NFPA *Standard* 96 calls for the exhaust fan to continue to run in the event of a fire unless fan shutdown is required by a listed component of the ventilating system or of the fire-extinguishing system. Dry and wet chemical fire-extinguishing systems protecting ductwork are tested both with and without airflow; exhaust airflow is not necessary for proper operation.

OPERATION AND MAINTENANCE

Operation

All components of the ventilation system are designed to operate in balance with each other, even under variable loads, to properly capture, contain, and remove cooking effluent and heat and maintain proper space temperature control in the most efficient and economical manner. Deterioration in any of these components unbalances the system, affecting one or more of its design concepts. The system design intent should be fully understood by the operator so that any deviations in operation can be noted and corrected. In addition to creating health and fire hazards, normal cooking effluent deposits can also unbalance the system, so they must be regularly removed.

All components of exhaust and replacement air systems affect proper capture, containment, and removal of cooking effluent. In the exhaust system, this includes the cooking equipment itself, exhaust hood, all filtration devices, ducts, exhaust fan, and any dampers. In

the replacement air system, this includes the air-handling unit(s) with intake louvers, dampers, filters, fan wheels, heating and cooling coils, ducts, and supply registers. In systems that obtain their replacement air from the general HVAC system, this also includes return air registers and ducts.

When the system is first set up and balanced in new condition, these components are set to optimum efficiency. In time, all components become dirty; filtration devices, dampers, louvers, heating and cooling coils, and ducts become restricted; fan blades change shape as they accumulate dirt and grease; and fan belts loosen. In addition, dampers can come loose and change position, even closing, and ducts can develop leaks or be blocked if internal insulation sheets fall down.

All these changes deteriorate system performance. The operator should know how the system performed when it was new, to better recognize when it is no longer performing the same way. This knowledge allows problems to be found and corrected sooner and the peak efficiency and safety of system operation to better be maintained.

Maintenance

Maintenance may be classified as preventive or emergency (breakdown). **Preventive maintenance** keeps the system operating as close as possible to optimal performance, including maximum production and least shutdown. It is the most effective maintenance and is preferred.

Preventive maintenance can prevent most emergency shutdowns and emergency maintenance. It has a modest ongoing cost and fewer unexpected costs. Clearly the lowest-cost maintenance in the long run, it keeps the system components in peak condition, extending the operating life of all components.

Emergency maintenance must be applied when a breakdown occurs. Sufficient staffing and money must be applied to the situation to bring the system back on line in the shortest possible time. Such emergencies can be of almost any nature. They are impossible to predict or address in advance, except to presume the type of component failures that could shut the system down and keep spares of these components on hand or readily accessible, so they can be quickly replaced. Preventive maintenance, which includes regular inspection of critical system components, is the most effective way to avoid emergency maintenance.

Following are brief descriptions of typical operations of various components of kitchen ventilation systems and the type of maintenance and cleaning required to bring the abnormally operating system back to normal. Many nontypical operations are not listed here.

Cooking Equipment

Normal Operation. Produces properly cooked product, of correct temperature, within expected time. Minimum smoke during cooking.

Abnormal Operation. Produces undercooked product, of lower temperature, with longer cooking times. Increased smoke during cooking.

Cleaning/Maintenance. Clean solid cooking surfaces between each cycle if possible, or at least once a day. Baked-on product insulates and retards heat transfer. Filter frying medium daily and change it on schedule recommended by supplier. Check that (1) fuel source is at correct rating, (2) thermostats are correctly calibrated, and (3) conditioned air is not blowing on cooking surface.

Solid-fuel appliances are listed as "Extra-Heavy Duty" (see Table 1) and require additional attention. A hood over a solid-fuel appliance must be individually vented and therefore not be combined at any point with another duct and fan system. Using a UL *Standard* 762 upblast, in-line, or utility set fan listed to 400 or 500°F is suggested because the airstream temperature may be hotter without cooler air combining from other, typically lower-temperature cooking appliances. Design, installation, and maintenance

precautions for the use of and emissions from solid fuel include monthly duct cleaning with weekly inspections, spark arrestors, and additional spacing to fryers. Refer to NFPA *Standard* 96, Chapters 5 to 10 and 14, and IMC sections 507 and 906, for additional direction.

Exhaust Systems

Normal Operation. All cooking vapors are readily drawn into the exhaust hood, where they are captured and removed from the space. The environment immediately around the cooking operation is clear and fresh.

Abnormal Operation. Many cooking vapors do not enter the exhaust hood at all, and some that enter subsequently escape. The environment around the cooking operation, and likely in the entire kitchen, is contaminated with cooking vapors and a thin film of grease.

Cleaning/Maintenance. Clean all grease removal devices in the exhaust system. Hood filters should be cleaned at least daily. For other devices, follow the minimum recommendations of the manufacturer; even these may not be adequate at very high flow rates or with products producing large amounts of effluent. Check that (1) all dampers are in their original position, (2) fan belts are properly tensioned, (3) the exhaust fan is operating at the proper speed and turning in the proper direction, (4) the exhaust duct is not restricted, and (5) the fan blades are clear.

NFPA *Standard* 96 design requirements for access to the system should be followed to facilitate cleaning the exhaust hood, ductwork, and fan. Cleaning should be done before grease has built up to 0.25 in. in any part of the system, and by a method that cleans to bare metal. Cleaning agents should be thoroughly rinsed off, and all loose grease particles should be removed, because they can ignite more readily. Agents should not be added to the surface after cleaning, because their textured surfaces merely collect more grease more quickly. Fire-extinguishing systems may need to be disarmed before cleaning, to prevent accidental discharge, and then reset by authorized personnel after cleaning. All access panels removed must be reinstalled after cleaning, with proper gasketing in place to prevent grease leaks and escape of fire.

Supply, Replacement, and Return Air Systems

Normal Operation. The environment in the kitchen area is clear, fresh, comfortable, and free of drafts and excessive air noise.

Abnormal Operation. The kitchen is smoky, choking, hot, and humid, and perhaps very drafty with excessive air noise.

Cleaning/Maintenance. Check that the replacement air system is operating and is providing the correct amount of air to the space. If it is not, the exhaust system cannot operate properly. Check that dampers are set correctly, filters and exchangers are clean, the belts are tight, the fan is turning in the correct direction, and supply and return ductwork and registers are open, with supply air discharging in the correct direction and pattern. If drafts persist, the system may need to be rebalanced. If noise persists in a balanced system, system changes may be required.

Filter cleaning or changing frequency varies widely depending on the quantity of airflow and contamination of local air. Once determined, the cleaning schedule must be maintained.

With replacement air systems, the air-handling unit, coils, and fan are usually cleaned in spring and fall, at the beginning of the seasonal change. More frequent cleaning or better-quality filtering may be required in some contaminated environments. Duct cleaning for the system is on a much longer cycle, but local codes should be checked as stricter requirements are invoked. Ventilation systems should be cleaned by professionals to ensure that none of the expensive system components are damaged. Cleaning companies should be required to carry adequate liability insurance. The Power Washers of North America (PWNA) and the International Kitchen Exhaust Cleaning

Association (IKECA) provide descriptions of proper cleaning and inspection techniques and lists of their members.

Control Systems (Operation and Safety)

Normal Operation. Control systems should not allow cooking equipment to operate unless both exhaust and replacement air systems are operating and the fire suppression system is armed. With multiple exhaust and replacement air systems, controls maintain the proper balance as cooking equipment is turned on and off. In the event that a fire-suppression system operates, the energy source for the cooking equipment it serves is shut off. On ducted systems, the exhaust fan usually keeps running to remove fire and smoke from building. On ductless systems, the fan may or may not keep running, but a discharge damper closes to keep the flames away from the ceiling. The replacement air system may continue to run, or it may be shut off by a separate local area fire and smoke sensor. If the control system does not operate in this way, changing to this operation should be considered.

Abnormal Operation. Cooking equipment operates when exhaust and supply are turned off, perhaps because the fire suppression system is unarmed or has been bypassed. When extra cooking systems are turned on or off, the operator must remember to manually turn the exhaust and replacement air fans on or off as well.

When exhaust and replacement air systems are not interlocked, the system can be out of balance. This can cause many of the kinds of abnormal operation described for the other systems. With gas-fired cooking equipment, the fire-suppression system may have a false discharge if the exhaust system is not operating. If cooking is allowed when the fire suppression system is inoperable, the chance of a serious fire is greater, and the operator is liable because insurance usually does not cover this situation.

Cleaning/Maintenance. Cleaning is usually restricted to mechanical operators and electrical sensors in the fire-suppression system and within the hood that are exposed to grease. If they become excessively coated with grease, mechanical operators cannot move and sensors cannot sense. The result is decreased control and safety. The mechanical operators should be cleaned as often as required to maintain free movement. Fire-suppression system operators may need to be changed annually rather than cleaned. Check with a local fire-suppression system dealer before attempting to clean any of these components.

Maintaining control systems (presuming they were properly designed) is mostly a matter of checking the performance of the entire system regularly (min. every 3 months) to ensure it is still performing as designed. Mechanical linkages on dampers and cleanliness of sensors should be checked regularly (min. once a month). All electrical screw terminals in the components should be checked for tightness, relay contacts should be checked for cleanliness, and all exposed conducting surfaces should be checked for corrosion on an annual basis.

RESIDENTIAL KITCHEN VENTILATION

Although commercial and residential cooking processes are similar, their ventilation requirements and procedures are different. Differences include exhaust airflow rate and installation height. In addition, residential kitchen ventilation is less concerned with replacement air, and energy consumption is comparatively insignificant because of lower airflow, smaller motors, and intermittent operation.

Equipment and Processes

Although the physics of cooking and the resulting effluent are about the same, residential cooking is usually done more conservatively. Heavy-duty and extra-heavy-duty equipment, such as upright broilers and solid-fuel-burning equipment (described in Table 1), is not used. Therefore, the high ventilation rates of commercial

kitchen ventilation and equipment for delivering these rates are not often found in residential kitchens. However, some residential kitchens are designed to operate with commercial-type cooking equipment, with higher energy inputs rates than usually found. In these cases, the hood may be similar to a commercial hood, and the required ventilation rate may approach that required for small commercial facilities.

Cooking effluent and by-products of open-flame combustion must be more closely controlled in a residence than in a commercial kitchen, because any escaping effluent can be dispersed throughout a residence, whereas a commercial kitchen is designed to be negatively pressurized compared to surrounding spaces. A residence also has a much lower background ventilation rate, making escaped contaminant more persistent. This situation makes residential kitchen ventilation a different kind of challenge, because problems cannot be resolved by simply increasing the ventilation rate at the cooking process.

Residential cooking always produces a convective plume that carries with it cooking effluent, often including grease vapor and particles, as well as water vapor, and by-products of combustion when natural gas is the energy source. Sometimes there is spatter as well, but those particles are so large that they are not removed by ventilation. Residential kitchen hoods depend more on thermal buoyancy than mechanical exhaust to capture cooking effluent and by-products of combustion.

Hoods and Other Ventilation Equipment

Wall-mounted, conventional range hoods ventilate most residential kitchens. Overall, they do the best job at the lowest installed cost. There are unlimited style-based variations of the conventional range hood shape. Deep canopy hoods are somewhat more effective because of their capture volume. Other styles have less volume, or a more flat bottom, and may be somewhat less effective at capturing effluent. To the extent that residential range hoods are often mounted between cabinets, with portions of the cabinets extending below the sides of the hood, performance may be improved because the cabinet sides help contain and channel the exhaust flow into the hood.

An increasingly popular development in residential kitchen ventilation is using a ventilating microwave oven in place of the typical residential range hood. Microwave ovens used for this purpose typically include small mesh filters mounted on the bottom of the oven and an internal exhaust fan. Means are usually provided to direct the exhaust flow in two directions: back into the kitchen or upward to an exhaust duct leading outdoors. The latter is more expensive but highly preferred; otherwise, if directed back to the kitchen, walls, ceiling, and cabinet surfaces are likely to become coated with grease from condensed grease vapor, and grease residue can damage paint and varnish. Additionally, typical microwave oven ventilators do not include vertical surfaces that provide a reservoir volume to contain the convective plume during transient effects, such as removing the lid from a cooking vessel. Consequently, microwave oven ventilators often provide lower exhaust capture and containment performance than standard range hoods.

Downdraft range-top ventilators have also become more popular. Functionally, these are an exception, because they capture contaminants by producing velocities over the cooking surface greater than those of the convective plume. With enough velocity, their operation can be satisfactory; however, velocity may be limited to prevent adverse effects such as gas flame disturbance and cooking process cooling. Additionally, this method is more effective for exhaust from cooking near the range surface, and it is usually much less effective for capturing the convective plume from taller cooking vessels, because the convective plume is too far above the ventilator intake to be affected by it.

Ironically, many high-end kitchens have less efficient ventilation than standard range hoods. Inefficient methods include

- Mounting range tops in cooking islands with no exhaust hood or other means of ventilation
- Mounting ovens in cabinets, separate from rangetops, without any way to remove heat and effluents from the oven
- Using low-profile exhaust devices with insufficient overhang over the appliance and no reservoir to contain convective plume during dynamic effects
- Having duct runs, particularly in larger homes, with very high static pressure losses, so that the actual exhaust flow rate is much lower than the nominal exhaust fan rating

Whole-kitchen exhaust fans were more common in the past, but they are still used. Mounted in the kitchen wall or ceiling, they ventilate the entire kitchen volume rather than capturing contaminants at the source. For kitchen exhaust fans not above the cooking surface, and without a capturing hood, 15 air changes per hour (ach) is recommended; for ceiling-mounted fans, this is usually sufficient, but for wall-mounted fans, it may be marginal.

Residential exhaust hoods are often furnished with multiple-speed fans, so that users can match exhaust fan speeds (and noise) with the cooking process and resultant convective plume. Carrying this concept further, at least one high-end residential exhaust hood manufacturer provides an automatic two-speed control that increases fan speed when higher convective plume temperature is sensed.

Continuous low-level, whole-building ventilation is increasingly used to ensure good indoor air quality in modern, tightly built houses with less infiltration. ASHRAE *Standard* 62.2 requires kitchen ventilation in most residences. Some whole-building ventilation systems can intermittently increase airflow to achieve the needed reduction in cooking effluent. In that case, there must be provision to avoid introducing and accumulating grease and other cooking effluent that may cause undesirable growth of microorganisms.

Differences Between Commercial and Residential Equipment

Residential hoods usually meet UL *Standard* 507 requirements. Fire-actuated dampers are never part of the hood and are almost never used. Grease filters in residential hoods are much simpler, and grease collection channels are rarely used because inadequate maintenance could allow grease to pool, creating a fire and health hazard.

Conventional residential wall hoods usually have standard dimensions that match the standard 3 in. modular grid of residential cabinets. Heights of 6, 9, 12, and 24 in. are common, as are depths from 17 to 22 in. Width is usually the same as the cooking surface, with 30 in. width nearly standard in the United States. Current U.S. Housing and Urban Development (HUD) Manufactured Home Construction and Safety Standards call for 3 in. overhang per side.

Hood mounting height is usually 18, 24, or 30 in., and sometimes even higher with a sacrifice in collection efficiency. A lower-mounted hood captures more effectively because there is less opportunity for lateral air currents to disrupt the convective plume. Studies show 18 in. is the minimum height for cooking surface access. Some codes require a minimum of 30 in. from the cooking surface to combustible cabinets. In that case, the bottom of a 6 in. hood can be 24 in. above the cooking surface.

A minimum airflow rate (exhaust capacity) of 40 cfm per linear foot of hood width has long been recommended by the Home Ventilating Institute (HVI 2004), and confirmed by field tests. Additional capacity, with speed control, is desirable for handling unusually vigorous cooking and cooking mistakes, because airflow can be briefly increased to clear the air, and speed can be reduced to a quieter level for normal cooking.

Exhaust Duct Systems

Residential hoods offer little opportunity for custom design of an exhaust system. The range hood has a built-in duct connector and the duct should be the same size, whether round or rectangular. A hood includes either an axial or a centrifugal fan. The centrifugal fan can develop higher pressure, but the axial fan is usually adequate for low-volume hoods. The great majority of residential hoods in the United States have HVI-certified airflow performance. In all cases, it is highly preferable to vent the exhaust hood outdoors through a roof cap, rather than venting into the attic or back into the home, whether into the kitchen or elsewhere.

Replacement (Makeup) Air

The exhaust rate of residential hoods is generally low enough and natural infiltration sufficient to avoid the need for replacement air systems. Although this may cause slight negative pressurization of the residence, it is brief and is usually less than that caused by other equipment. Still, backdrafts through the flue of a combustion appliance should be avoided and residences with gas furnace and water heater should have the flue checked for adequate flow. NFPA *Standard* 54 provides a method of testing flues for adequate performance. Sealed-combustion furnaces and water heaters are of less concern.

Sometimes commercial-style cooking equipment approved for residential use is installed in residences. For the higher ventilation requirements, see earlier sections of this chapter, especially the section on Replacement (Makeup) Air Systems.

Energy Conservation

The energy cost of residential hoods is quite low because of the few annual running hours and the low rate of exhaust. For example, it typically costs less than $10 per heating season in Chicago to run a hood and heat replacement air, based on running at 150 cfm for an hour a day and using gas heat.

Fire Protection for Residential Hoods

Residential hoods must be installed with metal (preferably steel) duct, positioned to prevent grease pooling. Residential hood exhaust ducts are almost never cleaned, and there is no evidence that this causes fires.

There have been some attempts to make fire extinguishers available in residential hoods, but none has met with broad acceptance. However, grease fires on the residential cooking surface continue to occur, almost always the result of unattended cooking. There is no industry-accepted performance standard or consistency of design in residential fire-extinguishing equipment.

Maintenance

All UL-listed hoods and kitchen exhaust fans are designed for cleaning, which should be done at intervals consistent with the cooking practices of the user. Although cleaning is sometimes thought to be for fire prevention, the health benefits of removing nutrients available for the growth of organisms can be more important.

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CHAPTER 32

GEOTHERMAL ENERGY

THE use of geothermal resources can be subdivided into three general categories: high-temperature (>300°F) electric power production, intermediate- and low-temperature (<300°F) direct-use applications, and ground-source heat pump applications (generally <90°F). This chapter covers only direct use (including wells, equipment, and applications) and ground-source heat pumps. Design aspects of the building heat pump loop may be found in Chapter 8 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*.

RESOURCES

Geothermal energy is the thermal energy within the earth's crust: thermal energy in rock and fluid (water, steam, or water containing large amounts of dissolved solids) that fills the pores and fractures within the rock, sand, and gravel. Calculations show that the earth, originating from a completely molten state, would have cooled and become completely solid many thousands of years ago without an energy input beyond that of the sun. It is believed that the ultimate source of geothermal energy is radioactive decay within the earth (Bullard 1973).

Through plate motion and vulcanism, some of this energy is concentrated at high temperature near the surface of the earth. Energy is also transferred from the deeper parts of the crust to the earth's surface by conduction and by convection in regions where geological conditions and the presence of water permit.

Because of variation in volcanic activity, radioactive decay, rock conductivities, and fluid circulation, different regions have different heat flows (through the crust to the surface), as well as different temperatures at a particular depth. The normal increase of temperature with depth (i.e., the normal geothermal gradient) is about 13.7°F per 1000 ft of depth, with gradients of 5 to 27°F per 1000 ft being common. The areas that have higher temperature gradients and/or higher-than-average heat flow rates constitute the most interesting and viable economic resources. However, areas with normal gradients may be valuable resources if certain geological features are present.

Geothermal resources of the United States are categorized into the following types:

Igneous point resources are associated with magma bodies, which result from volcanic activity. These bodies heat the surrounding and overlying rock by conduction and convection, as permitted by the rock permeability and fluid content in the rock pores.

Hydrothermal convection systems are hot fluids near the surface of the earth that result from deep circulation of water in areas of high regional heat flow. A widely used resource, these fluids have risen from natural convection between hotter, deeper formations and cooler formations near the surface. The passageway that provides for this deep convection must consist of adequately permeable fractures and faults.

The preparation of this chapter is assigned to TC 6.8, Geothermal Energy Utilization.

Geopressured resources, present widely in the Gulf Coast of the United States, consist of regional occurrences of confined hot water in deep sedimentary strata, where pressures of greater than 10,000 psi are common. This resource also contains methane, which is dissolved in the geothermal fluid.

Radiogenic heat sources exist in various regions as granitic plutonic rocks that are relatively rich in uranium and thorium. These plutons have a higher heat flow than the surrounding rock; if the plutons are blanketed by sediments of low thermal conductivity, an elevated temperature at the base of the sedimentary section can result. This resource has been identified in the eastern United States.

Deep regional aquifers of commercial value can occur in deep sedimentary basins, even in areas of only normal temperature gradient. For deep aquifers to be of commercial value, (1) basins must be deep enough to provide usable temperature levels at the prevailing gradient, and (2) permeability within the aquifer must be adequate for flow.

The thermal energy in geothermal resources exists primarily in the rocks and only secondarily in the fluids that fill the pores and fractures within them. Thermal energy is usually extracted by bringing to the surface the hot water or steam that occurs naturally in the open spaces in the rock. Where rock permeability is low, the energy extraction rate is low. In permeable aquifers, fluid produced may be injected back into the aquifer at some distance from the production well to pass through the aquifer again and recover some of the energy in the rock. Figure 1 indicates geothermal resource areas in the United States.

Temperature

The temperature of fluids produced in the earth's crust and used for their thermal energy content varies from below 40°F to 680°F. As indicated in Figure 1, local gradients also vary with geologic conditions. The lower value represents fluids used as the low-temperature energy source for heat pumps, and the higher temperature represents an approximate value for the HGP-A well at Hilo, Hawaii.

The following classification by temperature is used in the geothermal industry:

High temperature	$t > 300°F$
Intermediate temperature	$195°F < t < 300°F$
Low temperature	$t < 195°F$

Electric generation is generally not economical for resources with temperatures below about 300°F, which is the reason for the division between high- and intermediate-temperature. However, binary (organic Rankine cycle) power plants, with the proper set of circumstances, have demonstrated that it is possible to generate electricity economically above 230°F. In 1988, there were 86 binary plants worldwide, generating a total of 126.3 MW (Di Pippo 1988).

Geothermal resources at the lower temperatures are more common. The frequency by reservoir temperature of identified convective systems above 195°F is shown in Figure 2.
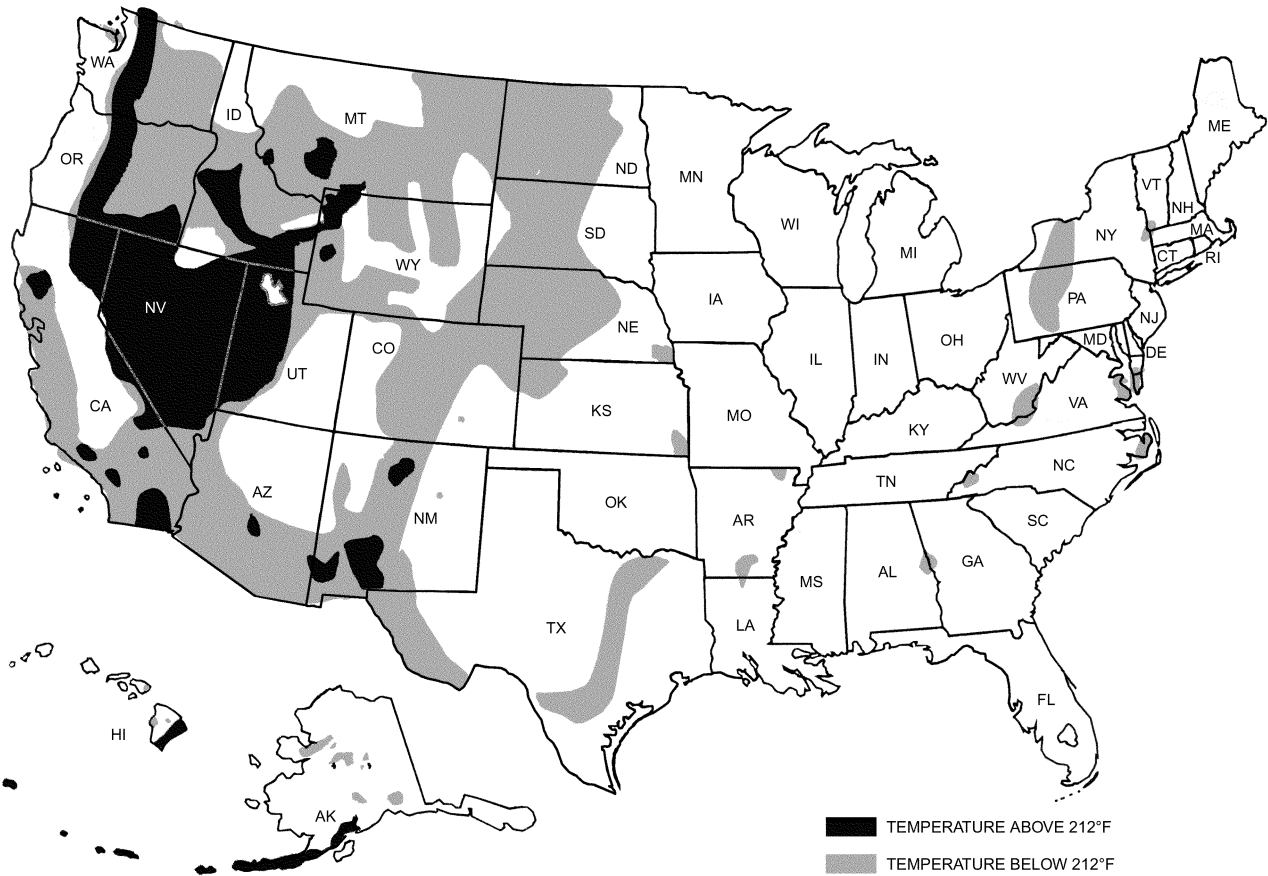
Fig. 1   **U.S. Hydrothermal Resource Areas**
(Lienau et al. 1995)

TEMPERATURE ABOVE 212°F

TEMPERATURE BELOW 212°F

LIVE GRAPH
Click here to view
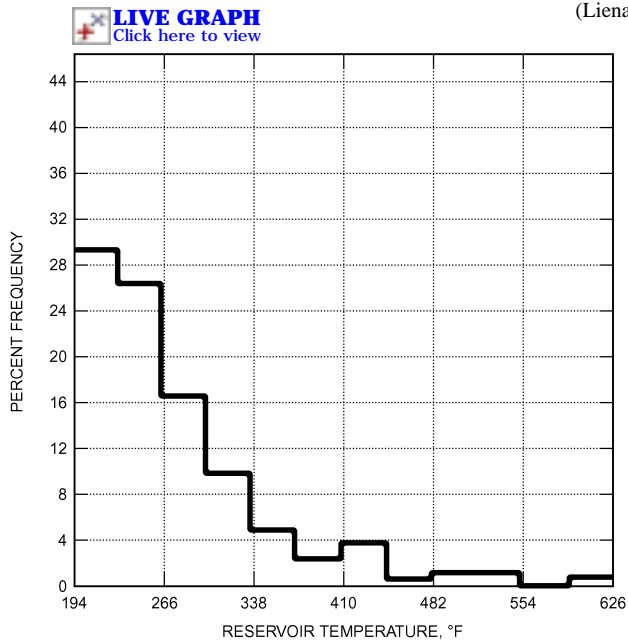
Fig. 2   **Frequency of Identified Hydrothermal Convection Resources Versus Reservoir Temperature**
(Muffler 1979)

Fluids

Geothermal energy is extracted from the earth through naturally occurring fluids in rock pores and fractures. Fluids produced are steam, hot water, or a two-phase mixture of both. These may contain various amounts of impurities, notably dissolved gases and dissolved solids.

Geothermal resources that produce essentially dry steam are **vapor-dominated**. Although these are valuable resources, they are rare. Hot-water (**fluid-dominated**) resources are much more common and can be produced either as hot water or as a two-phase mixture of steam and hot water, depending on the pressure maintained on the production well. If pressure in the production casing or in the formation around the casing is reduced below the saturation pressure at that temperature, some of the fluid will flash, and a two-phase fluid will result. If pressure is maintained above the saturation pressure, the fluid remains single-phase. In fluid-dominated resources, both dissolved gases and dissolved solids are significant.

Geothermal fluid chemistry varies over a wide range. In the Imperial valley of California, some high-temperature geothermal fluids may contain up to 300,000 ppm of total dissolved solids (TDS). Fluids of this character are extremely difficult to accommodate in systems design and materials selection. In fact, most low-temperature fluids contain less than 3000 ppm and many meet drinking water standards. Despite this, even geothermal fluids of a few hundred ppm TDS can cause substantial problems with standard construction materials.

Present Use

Discoveries of concentrated radiogenic heat sources and deep regional aquifers in areas of near-normal temperature gradient indicate that 37 states in the United States have economically exploitable direct-use geothermal resources (Interagency Geothermal Coordinating Council 1980). The Geysers, a resource area in northern

California, is the largest single geothermal development in the world.

The total electricity generated by geothermal development in the world was 7974 MW in 2000 (Lund et al. 2001). The direct application of geothermal energy for space heating and cooling, water heating, agricultural growth-related heating, and industrial processing represented about 51.6×10^9 Btu/h worldwide in 2000. In the United States in 2000, direct-use installed capacity amounted to 12.9×10^9 Btu/h, providing 19.3×10^{12} Btu/yr.

The major uses of geothermal energy in the United States are for heating greenhouse and aquaculture facilities. The principal industrial use of geothermal energy is for food processing.

DIRECT-USE SYSTEMS DESIGN

A major goal in designing direct-use systems is capturing the most possible heat from each gallon of fluid pumped. Owning and operating costs for the systems are composed primarily of well pumping and well capitalization components; maximizing system Δt (i.e., minimizing flow requirements) minimizes well capital cost and pump operating cost. In many cases, system design can benefit from connecting loads in series according to temperature requirements. Direct-use system design is covered in detail in Anderson and Lund (1980) and Rafferty (1989b).

Direct-use systems can be divided into four subsystems: (1) production, including the producing wellbore and associated wellhead equipment; (2) transmission and distribution to transport geothermal energy from the resource site to the user site and then distribute it to the individual user loads; (3) user system; and (4) disposal, which can be either surface disposal or injection back into a formation.

In a typical direct-use system, geothermal fluid is produced from the production borehole by a lineshaft multistage centrifugal pump. When the geothermal fluid reaches the surface, it is delivered to the application site through the transmission and distribution system.

In the system in Figure 3, geothermal fluid is separated from the heating system by a heat exchanger. This secondary loop is especially desirable when the geothermal fluid is particularly corrosive and/or causes scaling. The geothermal fluid is pumped directly back into the ground without loss to the surrounding surface.

COST FACTORS

The following characteristics influence the cost of energy delivered from geothermal resources:

- Well depth
- Distance between resource location and application site
- Well flow rate
- Resource temperature
- Temperature drop
- Load factor
- Composition of fluid
- Ease of disposal
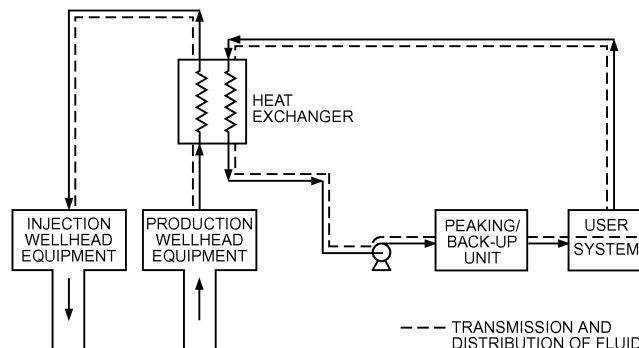
Many of these characteristics have a major influence because the cost of geothermal systems is primarily front-end capital cost; annual operating cost is relatively low.

Well Depth

The cost of the wells is usually one of the larger items in the overall cost of a geothermal system, and increases with resource depth. Compared to many geothermal areas worldwide, well depth requirements in the western United States are relatively shallow; most larger geothermal systems there operate with production wells of less than 2000 ft, and many at less than 1000 ft.

Distance Between Resource Location and Application Site

The direct use of geothermal energy must occur near the resource. The reason is primarily economic; although the geothermal (or secondary) fluid could be transmitted over moderately long distances (greater than 60 miles) without a great temperature loss, such transmission is generally not economically feasible. Most existing geothermal projects have transmission distances of less than 1 mile.

Well Flow Rate

Energy output from a production well varies directly with the fluid flow rate. The energy cost at the wellhead varies inversely with the well flow rate. A typical good resource has a production rate of 400 to 800 gpm per production well; however, geothermal direct-use wells have been designed to produce up to 2000 gpm.

Resource Temperature

The available temperature is fixed by the prevailing resource. The temperature can restrict applications. It often requires a reevaluation of accepted application temperatures, which were developed for uses served by conventional fuels for which the application temperature could be selected at any value in a relatively broad range. Most existing direct-use projects use fluids in the 130 to 230°F range.

Temperature Drop

Because well flow is limited, power output from a geothermal well is directly proportional to the geothermal fluid's temperature drop. Consequently, a larger temperature drop results in lower energy cost at the wellhead.

Cascading geothermal fluid to uses with lower temperature requirements can help achieve a large temperature difference (Δt). Most geothermal systems have been designed for a Δt between 30 and 50°F, although one system was designed for a Δt of 100°F with a 190°F resource temperature.

Load Factor

Defined as the ratio of the average load to the design capacity of the system, the load factor effectively reflects the fraction of time that the initial investment in the system is working. Again, because geothermal cost is primarily initial rather than operating cost, this factor significantly affects the viability of a geothermal system. As the load factor increases, so does the economy of using geothermal energy. The two main ways of increasing the load factor are (1) to select applications where it is naturally high, and (2) to use peaking equipment so that the geothermal design load is not the application peak load, but rather a reduced load that occurs over a longer period.

Composition of Fluid

The quality of the produced fluid is site specific and may vary from less than 1000 ppm TDS to heavily brined. Fluid quality influences two aspects of the design: (1) material selection to avoid

Fig. 3   Geothermal Direct-Use System with Wellhead Heat Exchanger and Injection Disposal

Table 1   Selected Chemical Species Affecting Fluid Disposal

Species	Reason for Control
Hydrogen sulfide (H_2S)	Odor
Boron (B^{3+})	Damage to agricultural crops
Fluoride (F^-)	Level limited in drinking water sources
Radioactive species	Levels limited in air, water, and soil

Source: Lunis (1989).

corrosion and scaling effects, and (2) disposal or ultimate end use of the fluid.

Ease of Disposal

The costs associated with disposal, particularly when injection is involved, can substantially affect development costs. Historically, most geothermal effluent was disposed of on the surface, including discharge to irrigation, rivers, and lakes. This method of disposal is considerably less expensive than constructing injection wells.

Geothermal fluids sometimes contain chemical constituents that make surface disposal problematic. Some of these constituents are listed in Table 1.

Most new, large geothermal systems use injection for disposal to minimize environmental concerns and ensure long-term resource reliability. If injection is chosen, the depth at which the fluid can be injected affects well cost substantially. Many jurisdictions require the fluid be returned to the same or similar aquifers; thus, it may be necessary to bore the injection well to the same depth as the production well. Direct-use injection wells are considered Class V wells under the U.S. Environmental Protection Agency's Underground Injection Control (UIC) program. Water wells, along with terminology relating to the technology, are discussed in the section on Groundwater Heat Pumps.

Direct-Use Water Quality Testing

Low-temperature geothermal fluids commonly contain seven key chemical species that can significantly corrode standard materials of construction (Ellis 1989). These include

- Oxygen (generally from aeration)
- Hydrogen ion (pH)
- Chloride ion
- Sulfide species
- Carbon dioxide species
- Ammonia species
- Sulfate ion

The principal effects of these species are summarized in Table 2. Except as noted, the described effects are for carbon steel. Kindle and Woodruff (1981) present recommended procedures for complete chemical analysis of geothermal well water.

Two of these species are not reliably detected by standard water chemistry tests and deserve special mention. Dissolved oxygen does not occur naturally in low-temperature (120 to 220°F) geothermal fluids that contain traces of hydrogen sulfide. However, because of slow-reaction kinetics, oxygen from air in-leakage may persist for some minutes. Once the geothermal fluid is produced, it is extremely difficult to prevent contamination, especially if pumps used to move the fluid are not downhole submersible or lineshaft turbine pumps. Even if fluid systems are maintained at positive pressure, air in-leakage at pump seals is likely, particularly with the low level of maintenance in many installations.

Hydrogen sulfide is ubiquitous in extremely low concentrations in geothermal fluids above 120°F. This corrosive species also occurs naturally in many cooler ground waters. For alloys such as cupronickel, which are strongly affected by it, hydrogen sulfide concentrations in the low parts per billion (10^9) range may have a serious detrimental effect, especially if oxygen is also present. At these levels, the characteristic rotten egg odor of hydrogen sulfide

Table 2   Principal Effects of Key Corrosive Species

Species	Principal Effects
Oxygen	• Extremely corrosive to carbon and low-alloy steels; 30 ppb shown to cause fourfold increase in carbon steel corrosion rate. • Concentrations above 50 ppb cause serious pitting. • In conjunction with chloride and high temperature, <100 ppb dissolved oxygen can cause chloride-stress corrosion cracking (chloride-SCC) of some austenitic stainless steels.
Hydrogen ion (pH)	• Primary cathodic reaction of steel corrosion in air-free brine is hydrogen ion reduction. Corrosion rate decreases sharply above pH 8. • Low pH (5) promotes sulfide stress cracking (SSC) of high-strength low-alloy (HSLA) steels and some other alloys coupled to steel. • Acid attack on cements.
Carbon dioxide species (dissolved carbon dioxide, bicarbonate ion, carbonate ion)	• Dissolved carbon dioxide lowers pH, increasing carbon and HSLA steel corrosion. • Dissolved carbon dioxide provides alternative proton reduction pathway, further exacerbating carbon and HSLA steel corrosion. • May exacerbate SSC. • Strong link between total alkalinity and corrosion of steel in low-temperature geothermal wells.
Hydrogen sulfide species (hydrogen sulfide, bisulfide ion, sulfide ion)	• Potent cathodic poison, promoting SSC of HSLA steels and some other alloys coupled to steel. • Highly corrosive to alloys containing both copper and nickel or silver in any proportions.
Ammonia species (ammonia, ammonium ion)	• Causes stress corrosion cracking (SCC) of some copper-based alloys.
Chloride ion	• Strong promoter of localized corrosion of carbon, HSLA, and stainless steel, as well as of other alloys. • Chloride-dependent threshold temperature for pitting and SCC. Different for each alloy. • Little if any effect on SSC. • Steel passivates at high temperature in 6070 ppm chloride solution (pH = 5) with carbon dioxide. 133,500 ppm chloride destroys passivity above 300°F.
Sulfate ion	• Primary effect is corrosion of cements.

Source: Ellis (1989).
Note: Except as indicated, described effects are for carbon steel.

may be absent, so field testing may be required for detection. Hydrogen sulfide levels down to 50 ppb can be detected using a simple field kit; however, absence of hydrogen sulfide at this low level may not preclude damage by this species.

Two other key species that should be measured in the field are pH and carbon dioxide concentrations. This is necessary because most geothermal fluids release carbon dioxide rapidly, causing a rise in pH.

Production of suspended solids (sand) from a well should be addressed during well construction with gravel pack, screen, or both. Proper selection of the screen/gravel pack is based on sieve analysis of cutting samples from drilling. Surface separation is less desirable because a surface separator requires sand to pass first through the pump, reducing its useful life.

Biological fouling is largely a phenomenon of low-temperature (<90°F) wells. The most prominent organisms are various strains (*Galionella*, *Crenothrix*) of what are commonly referred to as iron bacteria. These organisms typically inhabit water with a pH range of 6.0 to 8.0, dissolved oxygen content of less than 5 ppm, ferrous

iron content of less than 0.2 ppm, and a temperature of 46 to 61°F (Hackett and Lehr 1985). Iron bacteria can be identified microscopically. The most common treatment for iron bacteria infestation is chlorination, surging, and flushing; success depends on maintaining proper pH (less than 8.5), dosage, free residual chlorine content (200 to 500 ppm), contact time (24 h minimum), and agitation or surging. Precleaning (wire brushing) of the screen and redevelopment of the well after treatment are key to effectiveness. Hackett and Lehr (1985) provide additional detail on treatment.

MATERIALS AND EQUIPMENT

For system parts exposed to the fluid, materials selection is an important part of the design process. Chemical treatment of the geothermal fluid is not an effective strategy in most cases, because of economics and environmental (disposal) considerations. Corrosion and scaling in direct-use systems are generally addressed by isolating the fluid from the majority of the system using a plate heat exchanger.

Performance of Materials

Carbon Steel. The Ryznar index has traditionally been used to estimate the corrosivity and scaling tendencies of potable water supplies. However, one study found no significant correlation (at the 95% confidence level) between carbon steel corrosion and the Ryznar index (Ellis and Smith 1983). Therefore, the Ryznar and other indices based on calcium carbonate saturation should not be used to predict corrosion in geothermal systems, though they remain valid for scaling prediction.

In Class Va geothermal fluids [as described by Ellis (1989); <5000 ppm total key species (TKS), total alkalinity 207 to 1329 ppm as $CaCO_3$, pH 6.7 to 7.6] corrosion rates of about 5 to 20 mil/yr can be expected, often with severe pitting.

In Class Vb geothermal fluids [as described by Ellis (1989); <5000 ppm TKS, total alkalinity <210 ppm as $CACO_3$, pH 7.8 to 9.85], carbon steel piping has given good service in a number of systems, as long as system design rigorously excluded oxygen. However, introduction of 30 ppb oxygen under turbulent flow conditions causes a fourfold increase in uniform corrosion. Saturation with air often increases the corrosion rate by at least 15 times. Oxygen contamination at the 50 ppb level often causes severe pitting. Chronic oxygen contamination causes rapid failure.

External surfaces of buried steel pipe must be protected from contact with groundwater. Groundwater is aerated and has caused pipe failures by external corrosion. Required external protection can be obtained by coatings, pipe-wrap, or preinsulated piping, provided the selected material resists the system operating temperature and thermal stress.

At temperatures above 135°F, galvanizing (zinc coating) does not reliably protect steel from either geothermal fluid or groundwater. Hydrogen blistering can be prevented by using void-free (killed) steels.

Low-alloy steels (steels containing not more than 4% alloying elements) have corrosion resistance similar, in most respects, to carbon steels. As with carbon steels, sulfide promotes entry of atomic hydrogen into the metal lattice. If the steel exceeds a hardness of Rockwell C22, sulfide stress cracking may occur.

Copper and Copper Alloys. Copper-tubed fan-coil units and heat exchangers have consistently poor performance because of traces of sulfide species found in geothermal fluids in the United States. Copper tubing rapidly becomes fouled with cuprous sulfide films more than 1 mm thick. Serious crevice corrosion occurs at cracks in the film, and uniform corrosion rates of 2 to 6 mil/yr appear typical, based on failure analyses.

Experience in Iceland also indicates that copper is unsatisfactory for heat exchange service and that most brasses (Cu-Zn) and bronzes (Cu-Sn) are even less suitable. Cupronickel often performs more poorly than copper in low-temperature geothermal service because of trace sulfide.

Much less information is available regarding copper and copper alloys in non-heat-transfer service. Copper pipe shows corrosion behavior similar to copper heat exchange tubes under conditions of moderate turbulence (Reynolds numbers of 40,000 to 70,000). An internal inspection of yellow brass valves showed no significant corrosion. However, silicon bronze CA 875 (12-16Cr, 3-5Si, <0.05Pb, <0.05P), an alloy normally resistant to dealloying, failed in less than three years when used as a pump impeller. Leaded red brass (CA 836 or 838) and leaded red bronze (SAE 67) appear viable as pump internal parts. Based on a few tests at Class Va sites, aluminum bronzes have shown potential for corrosion in heavy-walled components (Ellis 1989).

Solder is yet another problem area for copper equipment. Lead-tin solder (50Pb, 50Sn) was observed to fail by dealloying after a few years' exposure. Silver solder (1Ag, 7P, Cu) was completely removed from joints in under two years. If the designer elects to accept this risk, solders containing at least 70% tin should be used.

Stainless Steel. Unlike copper and cupronickel, stainless steels are not affected by traces of hydrogen sulfide. Their most likely application is heat exchange surfaces. For economic reasons, most heat exchangers are probably of the plate-and-frame type, most of which are fabricated with one of two standard alloys, Type 304 and Type 316 austenitic stainless steel. Some pump and valve trim also are fabricated from these or other stainless steels.

These alloys are subject to pitting and crevice corrosion above a threshold chloride level, which depends on the chromium and molybdenum content of the alloy and on the temperature of the geothermal fluid. Above this temperature, the passivation film, which gives the stainless steel its corrosion resistance, is ruptured, and local pitting and crevice corrosion occur. Figure 4 shows the relationship between temperature, chloride level, and occurrence of localized corrosion of Type 304 and Type 316 stainless steel. This figure indicates, for example, that localized corrosion of Type 304 may occur in 80°F geothermal fluid if the chloride level exceeds approximately 210 ppm; Type 316 is resistant at that temperature until the chloride level reaches approximately 510 ppm. Because of its 2 to 3% molybdenum content, Type 316 is always more resistant to chlorides than is Type 304.

Aluminum. Aluminum alloys are not acceptable in most cases because of catastrophic pitting.
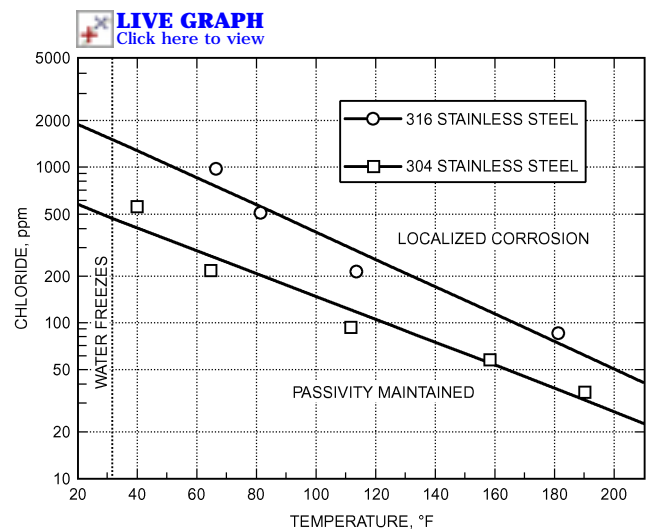
Fig. 4 Chloride Concentration Required to Produce Localized Corrosion of Stainless Steel as Function of Temperature
(Efrid and Moeller 1978)

Titanium. This material has extremely good corrosion resistance and could be used for heat exchanger plates in any low-temperature geothermal fluid, regardless of dissolved oxygen content. Great care is required if acid cleaning is to be performed. The vendor's instructions must be followed. The titanium should not be scratched with iron or steel tools; this can cause pitting.

Chlorinated Polyvinyl Chloride (CPVC) and Fiber-Reinforced Plastic (FRP). These materials are easily fabricated and are not adversely affected by oxygen intrusion. External protection against groundwater is not required. The mechanical properties of these materials at higher temperatures may vary greatly from those at ambient temperature, and the mechanical limits of the materials should not be exceeded. The usual mode of failure is creep rupture: strength decays with time. Manufacturer's directions for joining should be followed to avoid premature failure of joints.

Elastomeric Seals. Tests on O-ring materials in a low-temperature system in Texas indicated that a fluoroelastomer is the best material for piping of this nature; Buna-N is also acceptable (Ellis 1989). Neoprene, which developed extreme compression set, was a failure. Natural rubber and Buna-S should also be avoided. Ethylene-propylene terpolymer (EPDM) has been used successfully in gasket, O-ring, and valve seats in many systems. EPDM materials have swollen in some systems using oil-lubricated turbine pumps.

Pumps

Production well pumps are among the most critical components in a geothermal system and have been the source of much system downtime. Therefore, proper selection and design of the production well pump is extremely important. Well pumps are available for larger systems in two general configurations: lineshaft and submersible. The lineshaft type is most often used for direct-use systems (Rafferty 1989a).

Lineshaft Pumps. Lineshaft pumps are similar to those typically used in irrigation applications. An aboveground driver, typically an electric motor, rotates a vertical shaft extending down the well to the pump. The shaft rotates pump impellers in the pump bowl assembly, which is positioned at such a depth in the wellbore that adequate net positive suction head (NPSH) is available when the unit is operating. Two designs for the shaft/bearing portion of the pump are available: open and enclosed.

In the **open lineshaft pump**, the shaft bearings are supported in "spiders," which are anchored to the pump column pipe at 5 to 10 ft intervals. The shaft and bearings are lubricated by the fluid flowing up the pump column. In geothermal applications, bearing materials for open lineshaft designs are typically elastomer compounds. The shaft material is typically stainless steel. Experience with this design in geothermal applications has been mixed. It appears that the open lineshaft design is most successful in applications with high (<50 ft) static water levels or flowing artesian conditions. Open lineshaft pumps are generally less expensive than enclosed lineshaft pumps for the same application.

In an **enclosed lineshaft pump**, an enclosing tube protects the shaft and bearings from exposure to the pumped fluid. A lubricating fluid is admitted to the enclosed tube at the wellhead. It flows down the tube, lubricates the bearings, and exits where the column attaches to the bowl assembly. The bowl shaft and bearings are lubricated by the pumped fluid. Oil-lubricated, enclosed lineshaft pumps have the longest service life in low-temperature, direct-use applications.

These pumps typically include carbon or stainless steel shafts and bronze bearings in the lineshaft assembly, and stainless steel shafts and leaded red bronze bearings in the bowl assembly. Keyed-type impeller connections (to the pump shaft) are superior to collet-type connections (Rafferty 1989a).

Because of the lineshaft bearings, lineshaft pump reliability decreases as pump-setting depth increases. Nichols (1978) indicates that, below about 800 ft, reliability is questionable, even under good pumping conditions.

Submersible Pumps. The electrical submersible pump consists of three primary components located downhole: the pump, the drive motor, and the motor protector. The pump is a vertical multistage centrifugal type. The motor is usually a three-phase induction type that is filled with oil for cooling and lubrication; it is cooled by heat transfer to the pumped fluid moving up the well. The motor protector is located between the pump and the motor and isolates the motor from the well fluid while allowing pressure equalization between the pump intake and the motor cavity.

The electrical submersible pump has several advantages over lineshaft pumps, particularly for wells requiring greater pump bowl setting depths. The deeper the well, the greater the economic advantage of the submersible pump. Moreover, it is more versatile, adapting more easily to different depths.

Submersible pumps have not demonstrated acceptable lifetimes in most geothermal applications. Although they are commonly used in high-temperature, downhole applications in the oil and gas industry, the acceptable overhaul interval in that industry is much shorter than in a geothermal application. In addition, most submersibles operate at 3600 rpm, resulting in greater susceptibility to erosion in aquifers that produce moderate amounts of sand. They have, however, been applied in geothermal projects where an existing well of relatively small diameter must be used. At 3600 rpm, they provide greater flow capacity for a given bowl size than an equivalent 1750 rpm lineshaft pump.

Standard "cold-water" submersible motors can be used at temperatures up to approximately 120°F with adequate precautions. These consist primarily of ensuring adequate water velocity past the motor (minimum 3 ft/s), which may require the use of a sleeve, and a small degree of motor oversizing (Franklin Electric 2001).

Well Pump Control. Well pumps serving variable loads are often controlled using variable-speed drives (VSDs). Submersible pumps can also be controlled using VSDs, but special precautions are required. Drive-rated motors are not commonly available for these applications, so external electronic protection should be used to prevent premature motor failure. In addition, the motor manufacturer must be aware that the motor will applied in a variable-speed application. Finally, because of the large static head in many well pump applications, controls should be configured to prevent the pump from operating at no-flow conditions.

Heat Exchangers

Geothermal fluids can be isolated with large central heat exchangers, as in the case of a district heating system, or with exchangers at individual buildings or loads. In both cases, the principle is to isolate the geothermal fluid from complicated systems or those that cannot readily be designed to be compatible with the geothermal fluid. The principal types of heat exchangers used in transferring energy from the geothermal fluid are plate and downhole.

Plate Heat Exchangers. For all but the very smallest applications, plate and frame heat exchangers are the most commonly used design. Available in corrosion-resistant materials, easily cleanable, and able to accommodate increased loads through the addition of plates, these exchangers are well suited to geothermal applications. The high performance of plate heat exchangers is also an asset in many system designs. Because geothermal resource temperatures are often less than those used in conventional hot-water heating system design, minimizing temperature loss at the heat exchanger is frequently a design issue. Approach temperatures of 5°F and less are common.

Materials for plate heat exchangers in direct-use applications normally include Buna-N or EPDM gaskets and 316 or titanium plates. Plate selection is often a function of temperature and chloride content of the water. For applications characterized by chloride contents of >50 ppm at 200°F, titanium would be used. At lower temperatures, much higher chloride exposure can be tolerated (see Figure 4).

Downhole Heat Exchangers. The downhole heat exchanger (DHE) is an arrangement of pipes or tubes suspended in a wellbore (Culver and Reistad 1978). A secondary fluid circulates from the load through the exchanger and back to the load in a closed loop. The primary advantage of a DHE is that only heat is extracted from the earth, which eliminates the need to dispose of spent fluids. Other advantages are the elimination of (1) well pumps with their initial operating and maintenance costs, (2) the potential for depletion of groundwater, and (3) environmental and institutional restrictions on surface disposal. One disadvantage of a DHE is the limited amount of heat that can be extracted from or rejected to the well. The amount of heat extracted depends on the hydraulic conductivity of the aquifer and well design. Because of the limitations of natural convection, only about 10% of the heat output of the well is available from a DHE in comparison to pumping and using surface heat exchange (Reistad et al. 1979). With wells of approximately 200°F and depths of 500 ft, output under favorable conditions is sufficient to serve the needs of up to five homes.

The DHE in low- to moderate-temperature geothermal wells is installed in a casing, as shown in Figure 5.

Downhole heat exchangers with higher outputs rely on water circulation within the well, whereas lower-output DHEs rely on earth conduction. Circulation in the well can be accomplished by two methods: (1) undersized casing and (2) convection tube. Both methods rely on the difference in density between the water surrounding the DHE and that in the aquifer.

Circulation provides the following advantages:

- Water circulates around the DHE at velocities that, in optimum conditions, can approach those in the shell of a shell-and-tube exchanger.
- Hot water moving up the annulus heats the upper rocks and the well becomes nearly isothermal.
- Some of the cool water, being more dense than the water in the aquifer, sinks into the aquifer and is replaced by hotter water, which flows up the annulus.

Figure 5 shows well construction in competent formation (i.e., where the wellbore will stand open without a casing). An undersized casing with perforations at the lowest producing zone (usually near the bottom) and just below the static water level is installed. A packer near the top of the competent formation allows installation of an annular seal between it and the surface. When the DHE is installed and heat extracted, thermosiphoning causes cooler water inside the casing to move to the bottom, and hotter water moves up the annulus outside the casing.
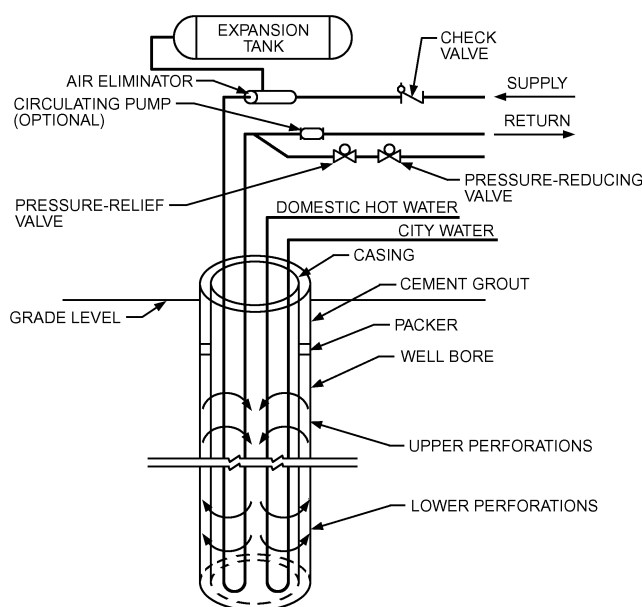
Because most DHEs are used for space heating (an intermittent operation), the heated rocks in the upper portion of the well store heat for the next cycle.

Where the well will not stand open without casing, a convection tube can be used. This is a pipe one-half the diameter of the casing either hung with its lower end above the well bottom and its upper end below the surface or set on the bottom with perforations at the bottom and below the static water level. If a U-bend DHE is used, it can be either inside or outside the convection tube. DHEs operate best in aquifers with a high hydraulic conductivity and that provide water movement for heat and mass transfer.

Valves

In large (>2.5 in.) pipe sizes, resilient-lined butterfly valves are preferred for geothermal applications. The lining material protects the valve body from exposure to the geothermal fluid. The rotary rather than reciprocating motion of the stem makes the valve less susceptible to leakage and build-up of scale deposits. For many direct-use applications, these valves are composed of Buna-N or EPDM seats, stainless steel shafts, and bronze or stainless steel disks. Where oil-lubricated well pumps are used, a seat material of oil-resistant material is recommended. Gate valves have been used in some larger geothermal systems but have been subject to stem leakage and seizure. After several years of use, they are no longer capable of 100% shutoff.

Piping

Piping in geothermal systems can be divided into two broad groups: pipes used inside buildings and those used outside, typically buried. Indoor piping carrying geothermal water is usually limited to the mechanical room, and is generally the same as that used in other hydronic applications, except for the materials. Because of the corrosive effects of hydrogen sulfide, copper piping is inappropriate; primarily carbon steel is used for these applications.

For buried piping, many existing systems have used some form of nonmetallic piping, particularly asbestos cement and fiberglass. Asbestos cement is no longer available. With the cost of fiberglass for larger sizes (>6 in.) sometimes prohibitive, ductile iron is frequently used. Available in sizes >2 in., ductile iron offers several positive characteristics: low cost, familiarity to installation crews, and wide availability. It requires no allowances for thermal expansion if push-on fittings are used.

Most larger-diameter buried piping is pre-insulated. The basic ductile iron pipe is surrounded by a layer of insulation (typically polyurethane), which is protected by an outer jacket of PVC or PE.

The standard ductile iron product used for municipal water systems is sometimes modified for geothermal use. The seal coat used to protect the cement lining of the pipe is not suitable for the temperature of most geothermal applications; in applications where the geothermal water is especially soft or low in pH, the cement lining should be omitted as well. Special high-temperature gaskets (usually EPDM) are used in geothermal applications. Few problems have been encountered in the use of ferrous piping with low-temperature geothermal fluids unless high chloride concentration, low (<7.0) pH, or oxygen is present in the fluid. Most cases of corrosion failure have resulted from external attack due to soil moisture in buried applications.

**Fig. 5   Typical Connection of Downhole Heat Exchanger
for Space and Domestic Hot-Water Heating**
(Reistad et al. 1979)

RESIDENTIAL AND COMMERCIAL BUILDING APPLICATIONS

The primary applications for direct use of geothermal energy in the residential and commercial area are space and domestic water heating. Space cooling using the absorption process is possible but rarely applied.

Space Heating

Figure 6 illustrates a system that uses geothermal fluid at 170°F (Austin 1978). The geothermal fluid is used in two main equipment components for heating the buildings: (1) a plate heat exchanger that supplies energy to a closed heating loop previously heated by a natural gas boiler (the boiler remains as a standby unit) and (2) a water-to-air coil used for preheating ventilation air. In this system, proper control is crucial for economical operation.

The average temperature of discharged fluid is 120 to 130°F. Geothermal fluid is used directly in the preheat coils in the buildings, which would probably not be the case if the system were designed today (Lienau 1979).

Figure 7 shows a geothermal district heating system that is unique in terms of its design based on a peak load Δt of 100°F using a 190°F resource. It is of closed-loop design with central heat exchangers. The production well has an artesian shut-in pressure of 25 psi, so the system operates with no production pump for most of the year. During colder weather, a surface centrifugal pump located at the wellhead boosts the pressure.

Geothermal flow from the production well is initially controlled by a throttling valve on the supply line to the main heat exchanger,

which responds to a temperature signal from the supply water on the closed-loop side of the heat exchanger. When the throttling valve has reached the full-open position, the production booster pump is enabled. The pump is controlled through a variable-speed drive that responds to the same supply-water signal as the throttling valve. The booster pump is designed for a peak flow rate of 300 gpm of 190°F water.

A few district heating systems have also been installed using an open distribution system. In this design, central heat exchangers (as
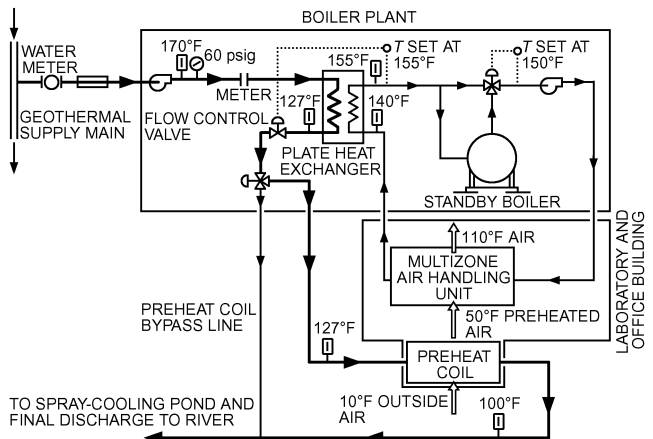
Fig. 6   Heating System Schematic
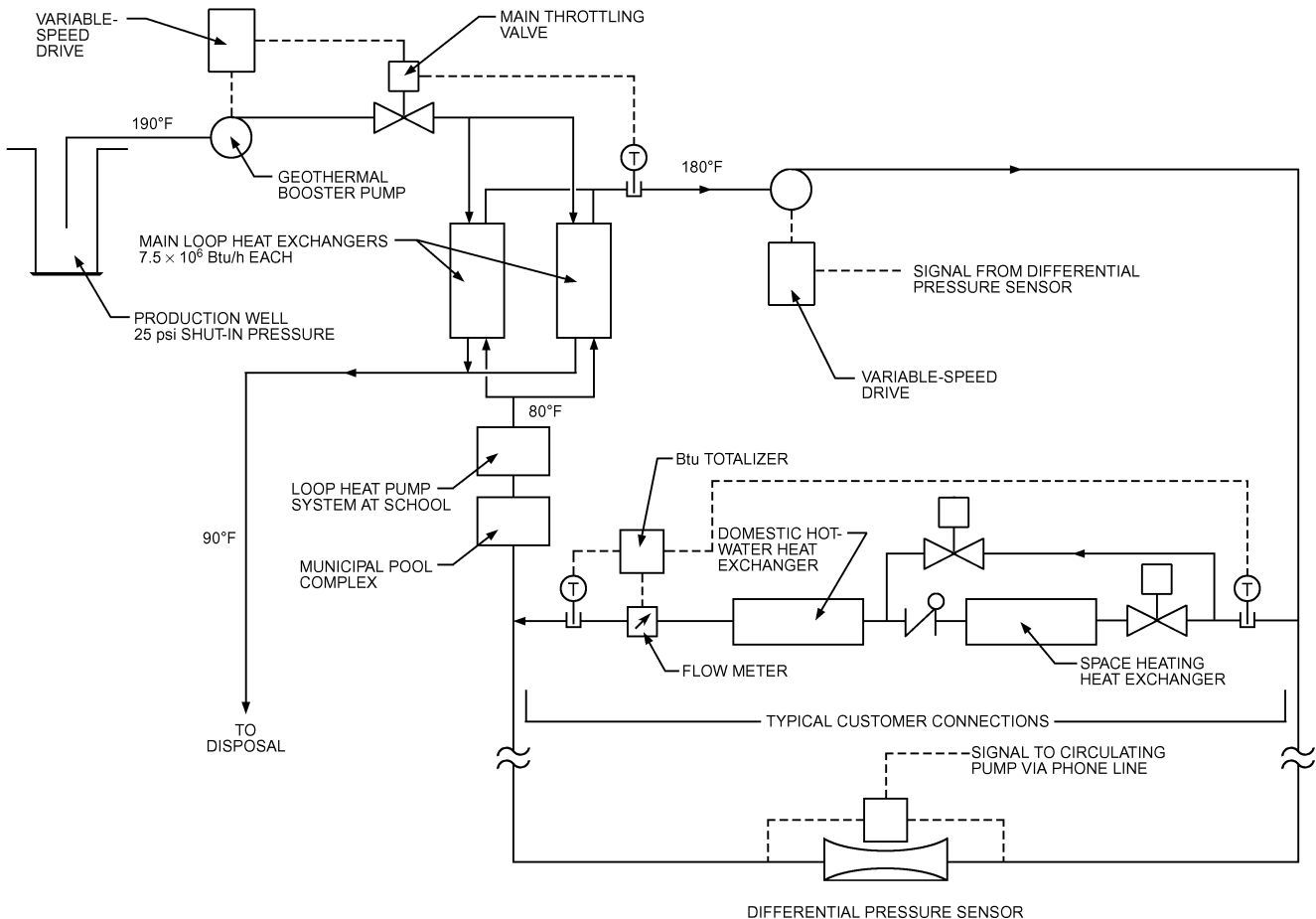
Fig. 7   Closed Geothermal District Heating System
(Rafferty 1989a)

in Figure 7) are eliminated and the geothermal water is delivered to individual building heat exchangers. When more than a few buildings are connected to the system, using central heat exchangers is normally more cost-effective.

Terminal equipment used in geothermal systems is the same as that used in nongeothermal heating systems. However, certain types of equipment are better suited to geothermal design than others.

In many cases, buildings heated by low-temperature geothermal sources operate at lower supply water temperatures than conventional hydronic designs. Because many geothermal sources are designed to take advantage of a large Δt, proper selection of equipment with respect to low flow and low temperature is important.

Finned-coil, forced-air systems generally function best in this low-temperature/high-Δt situation. One or two additional rows of coil depth compensate for the lower supply water temperature. Although an increased Δt affects coil circuiting, it improves controllability. This type of system should be able to use a supply water temperature as low as 110°F.

Radiant floor panels are well suited to very low water temperatures, particularly in industrial applications with little or no floor covering. In industrial settings, with a bare floor and a relatively low space-temperature requirement, the average water temperature could be as low as 95°F. For a higher space temperature and/or thick floor coverings, a higher water temperature may be required.

Baseboard convectors and similar equipment are the least capable of operating at low supply-water temperature. At 150°F average water temperatures, derating factors for this design load may be affected. This type of equipment can be operated at low temperatures from the geothermal source to provide base-load heating. Peak load can be supplied by a conventional boiler.

Domestic Water Heating

Domestic water heating in a district space-heating system is beneficial because it increases the overall size of the energy load, energy demand density, and load factor. For those resources that cannot heat water to the required temperature, preheating is usually possible. Whenever possible, the domestic hot-water load should be placed in series with the space-heating load to reduce system flow rates and increase Δt.

Space Cooling

Geothermal energy has seldom been used for cooling, although emphasis on solar energy and waste heat has created interest in cooling with thermal energy. The absorption cycle is most often used, and lithium bromide/water absorption machines are available in a wide range of capacities. Temperature and flow requirements for absorption chillers run counter to the general design philosophy for geothermal systems: they require high supply water temperatures and a small Δt on the hot-water side. Figure 8 illustrates the effect of reduced supply water temperature on machine performance. The machine is rated at a 240°F input temperature, so derating factors must be applied if the machine is operated below this temperature. For example, operation at a 200°F supply water temperature results in a 50% decrease in capacity, which seriously affects the economics of absorption cooling at a low resource temperature.

Coefficient of performance (COP) is less seriously affected by reduced supply water temperature. The nominal COP of a single-stage machine at 240°F is 0.65 to 0.70; that is, for each ton of cooling output, a heat input of 12,000 Btu/h divided by 0.65, or 18,460 Btu/h, is required.

Most absorption equipment is designed for steam input (an isothermal process) to the generator section. When this equipment is operated from a hot-water source, a relatively small Δt must be used. This creates a mismatch between building flow requirements for space heating and cooling. For example, assume a 200,000 ft² building is to use a geothermal resource for heating and cooling. At
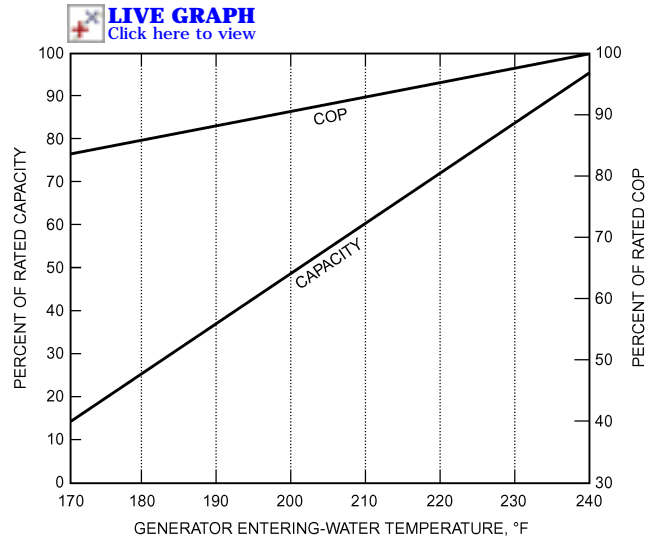
Fig. 8 Typical Lithium Bromide Absorption Chiller Performance Versus Temperature
(Christen 1977)

25 Btu/h·ft² and a design Δt of 40°F, the flow requirement for heating is 250 gpm. At 30 Btu/h·ft², a Δt of 15°F, and a COP of 0.65, the flow requirement for cooling is 1230 gpm.

Some small-capacity (3 to 25 ton) absorption equipment has been optimized for low-temperature operation in conjunction with solar heat. Although this equipment could be applied to geothermal resources, the prospects are questionable. Small absorption equipment generally competes with package direct-expansion units in this range; absorption equipment requires a great deal more mechanical auxiliary equipment for a given capacity. The cost of the chilled-water piping, pump, and coil; cooling-water piping, pump, and tower; and hot-water piping raises the capital cost of the absorption equipment substantially. Only in large sizes (>10 tons) and in areas with high electric rates and high cooling requirements (>2000 full-load hours) would this type of equipment offer an attractive investment to the owner (Rafferty 1989b).

INDUSTRIAL APPLICATIONS

Design philosophy for the use of geothermal energy in industrial applications, including agricultural facilities, is similar to that for space conditioning. However, these applications have the potential for much more economical use of the geothermal resource, primarily because they (1) operate year-round, which gives them greater load factors than possible with space-conditioning applications; (2) do not require an extensive (and expensive) distribution to dispersed energy consumers, as is common in district heating; and (3) often require various temperatures and, consequently, may be able to make greater use of a particular resource than space conditioning, which is restricted to a specific temperature. In the United States, the primary non-space-heating applications of direct-use geothermal resources are dehydration (primarily vegetables), gold mining, and aquaculture.

GROUND-SOURCE HEAT PUMPS

Ground-source heat pumps were originally developed in the residential arena and are now widely applied in the commercial sector. Many of the installation recommendations and design guides appropriate to residential design must be amended for large buildings. Caneta Research (1995) and Kavanaugh and Rafferty (1997) provide a more complete overview of design of ground-source heat pump systems. Kavanaugh (1991) and OSU (1988a, 1988b) provide a more detailed treatment of the design and installation of ground-source heat pumps, but their focus is primarily residential and light

commercial applications. Comprehensive coverage of commercial and institutional design and construction of ground-source heat pump systems is provided in CSA *Standard* C448.2.

TERMINOLOGY

The term **ground-source heat pump (GSHP)** is applied to a variety of systems that use the ground, groundwater, or surface water as a heat source and sink. The general terms include **ground-coupled (GCHP)**, **groundwater (GWHP)**, and **surface water (SWHP) heat pumps**. Many parallel terms exist [e.g., **geothermal heat pumps (GHP)**, earth energy systems, and ground-source (GS) systems] and are used to meet a variety of marketing or institutional needs (Kavanaugh 1992). See Chapter 8 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment* for a discussion of the merits of various other nongeothermal heat sources/sinks.

This chapter focuses primarily on the ground-loop portion of GSHP systems, although the heat pump units used in these systems are unique to GSHP technology as well. All GSHP systems use extended-range heat pump units, in most cases of water-to-air configuration. Extended range refers to the fact that the units are specifically designed for operation at entering water temperatures between 25°F in heating mode and 100°F in cooling mode. Units not meeting the extended range criteria are not suitable for use in GSHP systems.

Ground-Coupled Heat Pump Systems

The GCHP is a subset of the GSHP and is often called a closed-loop heat pump. A GCHP system consists of a reversible vapor compression cycle that is linked to a closed ground heat exchanger buried in soil (Figure 9). The most widely used unit is a water-to-air heat pump, which circulates a water or a water/antifreeze solution through a liquid-to-refrigerant heat exchanger and a buried thermoplastic piping network. A second type of GCHP is the direct-expansion (DX) GCHP, which uses a buried copper piping network through which refrigerant is circulated. To distinguish them from DX GCHPs, systems using water-to-air and water-to-water heat pumps are often referred to as GCHPs with secondary solution loops.

The GCHP is further subdivided according to ground heat exchanger design: vertical and horizontal. **Vertical** GCHPs (Figure

10) generally consist of two small-diameter, high-density polyethylene (HDPE) tubes that have been placed in a vertical borehole that is subsequently filled with a solid medium. The tubes are thermally fused at the bottom of the bore to a close return U-bend. Vertical tubes range from 0.75 to 1.5 in. nominal diameter. Bore depths range from 50 to 600 ft, depending on local drilling conditions and available equipment.

To reduce thermal interference between individual bores, a minimum borehole separation distance of 20 ft is recommended when loops are placed in a grid pattern. This distance may be reduced when bores are placed in a single row, the annual heating load is much greater than the annual cooling load, or vertical water movement mitigates the effect of heat buildup in the loop field.

Advantages of the vertical GCHP are that it (1) requires relatively small plots of ground, (2) is in contact with soil that varies very little in temperature and thermal properties, (3) requires the smallest amount of pipe and pumping energy, and (4) can yield the most efficient GCHP system performance. Disadvantages are (1) typically higher cost because of expensive equipment needed to drill the borehole and (2) the limited availability of contractors to perform such work.

Hybrid systems are a variation of ground-coupled systems in which a smaller ground loop is used, augmented during the cooling mode by a cooling tower. This approach can have merit in large cooling-dominated applications. The ground loop is sized to meet
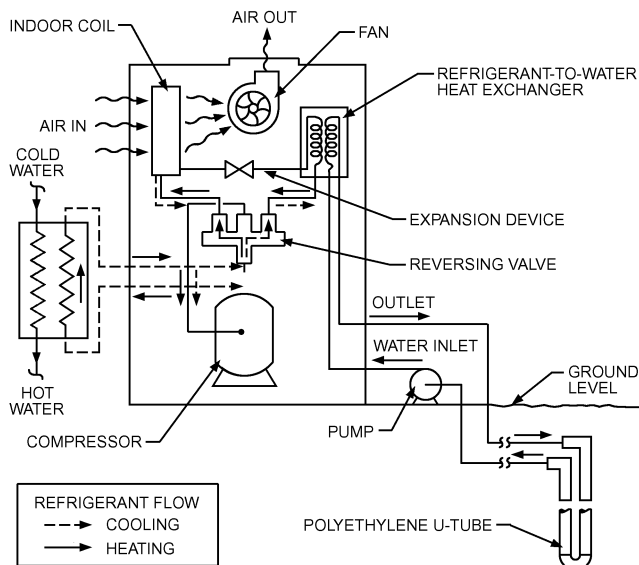
Fig. 9 Vertical Closed-Loop Ground-Coupled Heat Pump System
(Kavanaugh 1985)
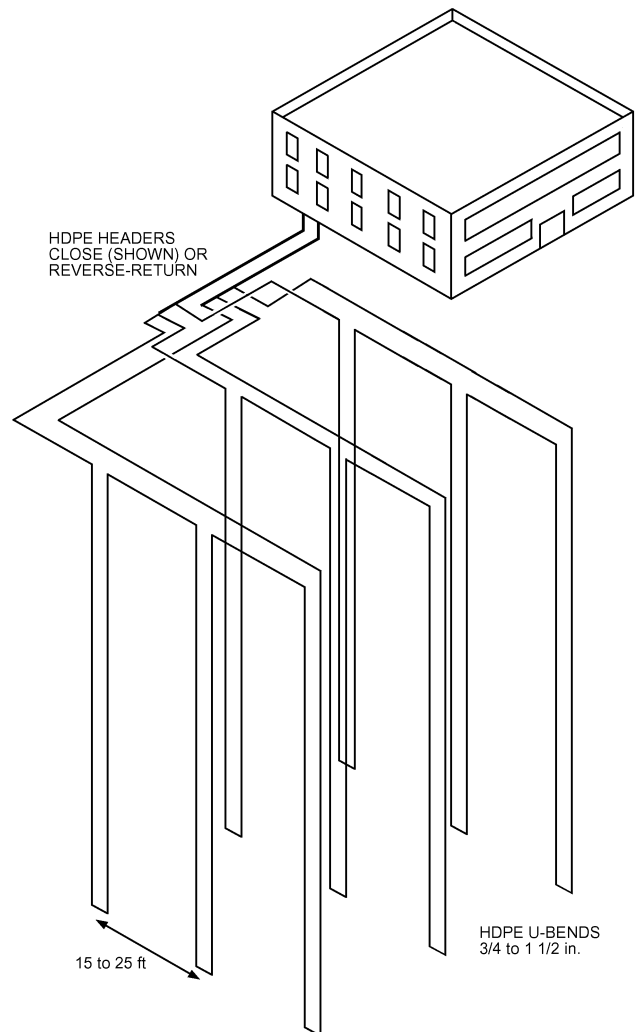
Fig. 10 Vertical Ground-Coupled Heat Pump Piping

the heating requirements. The downsized loop is used in conjunction with the cooling tower (usually the closed-circuit fluid cooler type) to meet the heat rejection load. Use of the tower reduces the capital cost of the ground loop in such applications, but somewhat increases maintenance requirements. For heavily heating-dominant applications, a downsized loop also can be augmented with an auxiliary heat source such as solar collectors or a boiler.

Horizontal GCHPs (Figure 11) can be divided into at least three subgroups: single-pipe, multiple-pipe, and spiral. Single-pipe horizontal GCHPs were initially placed in narrow trenches at least 4 ft deep. These designs require the greatest amount of ground area. Multiple pipes (usually two, four, or six), placed in a single trench, can reduce the amount of required ground area. Trench length is reduced with multiple-pipe GCHPs, but total pipe length must be increased to overcome thermal interference from adjacent pipes. The spiral coil is reported to further reduce required ground area. These horizontal ground heat exchangers are made by stretching small-diameter polyethylene tubing from the tight coil in which it is shipped into an extended coil that can be placed vertically in a narrow trench or laid flat at the bottom of a wide trench. Recommended trench lengths are only 20 to 30% of single-pipe horizontal GCHPs, but trenches may need to be twice this length to achieve equivalent thermal performance.

Advantages of horizontal GCHPs are that (1) they are typically less expensive than vertical GCHPs because relatively low-cost installation equipment is widely available, (2) many residential applications have adequate ground area, and (3) trained equipment operators are more widely available. Disadvantages include, in addition to a larger ground area requirement, greater adverse variations in performance because (1) ground temperatures and thermal properties fluctuate with season, rainfall, and burial depth, (2) slightly higher pumping-energy requirements, and (3) lower system efficiencies. OSU (1988a, 1988b) and Svec (1990) cover the design and installation of horizontal GCHPs.

Groundwater Heat Pump Systems

The second subset of GSHPs is groundwater heat pumps (Figure 12). Until the development of GCHPs, they were the most widely used type of GSHP. In the commercial sector, GWHPs can be an attractive alternative because large quantities of water can be delivered from and returned to relatively inexpensive wells that require very little ground area. Whereas the cost per unit capacity of the ground heat exchanger is relatively constant for GCHPs, the cost per unit capacity of a well water system is much lower for a large GWHP system. A single pair of high-volume wells can serve an entire building. Properly designed groundwater loops with well-developed water wells require no more maintenance than conventional air and water central HVAC. When groundwater is injected back into the aquifer by a second well, net water use is zero.
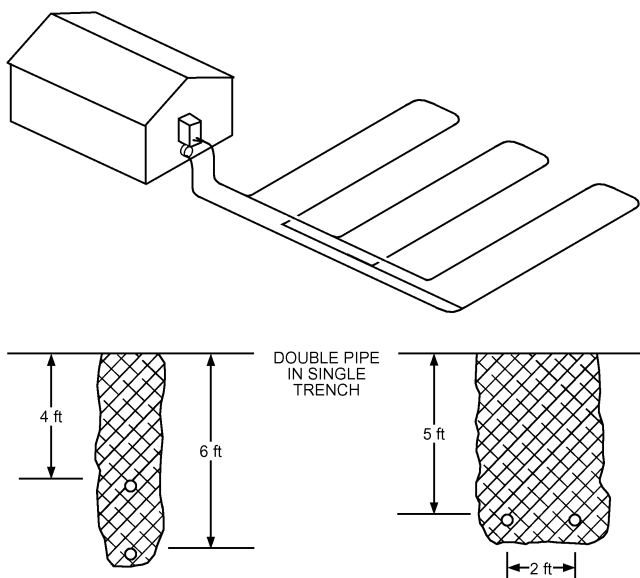
One widely used design places a central water-to-water heat exchanger between the groundwater and a closed water loop which is connected to water-to-air heat pumps located in the building. A second possibility is to circulate groundwater through a heat recovery chiller (isolated with a heat exchanger), and to heat and cool the building with a distributed hydronic loop.

Both types and other variations may be suited for direct preconditioning in much of the United States. Groundwater below 60°F can be circulated directly through hydronic coils in series or in parallel with heat pumps. The cool groundwater can displace a large amount of energy that would otherwise have to be generated by mechanical refrigeration.

Advantages of GWHPs under suitable conditions are (1) they cost less than GCHP equipment, (2) the space required for the water well is very compact, (3) water well contractors are widely available, and (4) the technology has been used for decades in some of the largest commercial systems.

Disadvantages are that (1) local environmental regulations may be restrictive, (2) water availability may be limited, (3) fouling precautions may be necessary if groundwater is used directly in the heat pumps and water quality is poor, and (4) pumping energy may be high if the system is poorly designed or draws from a deep aquifer.

Surface Water Heat Pump Systems

Surface water heat pumps have been included as a subset of GSHPs because of the similarities in applications and installation methods. SWHPs can be either closed-loop systems similar to GCHPs or open-loop systems similar to GWHPs. However, the thermal characteristics of surface water bodies are quite different

Fig. 11   Horizontal Ground-Coupled Heat Pump Piping
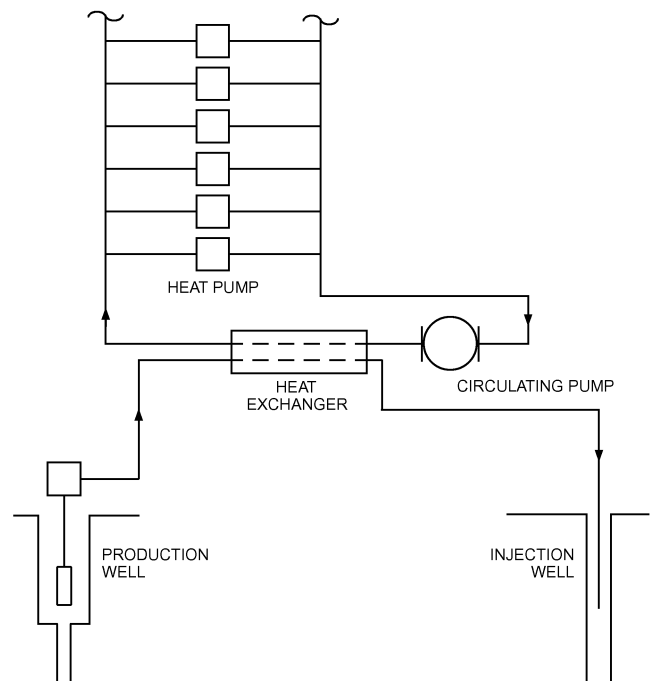
Fig. 12   Unitary Groundwater Heat Pump System

than those of the ground or groundwater. Some unique applications are possible, though special precautions may be warranted.

Closed-loop SWHPs (Figure 13) consist of water-to-air or water-to-water heat pumps connected to a piping network placed in a lake, river, or other open body of water. A pump circulates water or a water/antifreeze solution through the heat pump water-to-refrigerant heat exchanger and the submerged piping loop, which transfers heat to or from the body of water. The recommended piping material is thermally fused HDPE tubing with ultraviolet (UV) radiation protection.

Advantages of closed-loop SWHPs are (1) relatively low cost (compared to GCHPs) because of reduced excavation costs, (2) low pumping-energy requirements, (3) low maintenance requirements, and (4) low operating cost. Disadvantages are (1) the possibility of coil damage in public lakes and (2) wide variation in water temperature with outdoor conditions if lakes are small and/or shallow. Such variation in water temperature would cause undesirable variations in efficiency and capacity, though not as severe as with air-source heat pumps.

Open-loop SWHPs can use surface water bodies the way cooling towers are used, but without the need for fan energy or frequent maintenance. In warm climates, lakes can also serve as heat sources during winter heating mode, but in colder climates where water temperatures drop below 45°F, closed-loop systems are the only viable option for heating.

Lake water can be pumped directly to water-to-air or water-to-water heat pumps or through an intermediate heat exchanger that is connected to the units with a closed piping loop. Direct systems tend to be smaller, having only a few heat pumps. In deep lakes (40 ft or more), there is often enough thermal stratification throughout the year that direct cooling or precooling is possible. Water can be pumped from the bottom of deep lakes through a coil in the return air duct. Total cooling is possible if water is 50°F or below. Precooling is possible with warmer water, which can then be circulated through the heat pump units.

Site Characterization

Site characteristics influence the type of GSHP system most suitable for a particular location. Site characterization is the evaluation of a site's geology and hydrogeology with respect to its effect on GSHP system design. Important issues include presence or absence of water, depth to water, water (or soil/rock) temperature, depth to rock, rock type, and the nature and thickness of unconsolidated materials overlying the rock. Information about the nature of water resources at the site helps to determine whether an open-loop

system may be possible. Depth to water affects pumping energy for an open-loop system and possibly the type of rig used for drilling closed-loop boreholes. Groundwater temperature in most locations is the same as the undisturbed ground temperature. These temperatures are key inputs to the design of GSHP systems. The types of soil and rock allow a preliminary evaluation of the range of thermal conductivity/diffusivity that might be expected. The thickness and nature of the unconsolidated (soil, gravel, sand, clay, etc.) materials overlying the rock can influence whether casing will be required in the upper portion of boreholes for closed-loop systems, a factor which increases drilling cost.

After the GSHP system type has been decided, specific details about the subsurface materials' (rock/soil) thermal conductivity and diffusivity, water well static and pumping levels, drawdown, etc., are necessary to design the system. Ways to obtain these more detailed data are discussed in other parts of this chapter.

There are many sources for gathering site characterization information, such as geologic and hydrologic maps, state geology and water regulatory agencies, the U.S. Geological Survey (USGS 2000), and any information that may be available from geotechnical studies of the site. Among the best sources of information are water well completion reports for nearby water wells. These reports are filed by the driller upon completion of a water well and provide a great deal of information of interest for both open- and closed-loop designs. The most thorough versions of well completion reports (level of detail varies by state) cover all of the issues of interest listed at the beginning of this section. Information about access to and interpretation of these reports and other sources of information for site characterization is included in Rafferty (2000a) and Sachs (2002).

Once the type of system has been selected, more site-specific tests (ground thermal properties test for GCHP or well flow test for GWHP) can be used to determine the parameters necessary for system design.

Commissioning GSHP Systems

The design phase of GSHP commissioning requires a thorough site survey and characterization, accurate load modeling, and ensuring that the design chosen (and its documentation) meets the design intent.

The construction phase is dominated by observation of installation and verification of prefunctional checks and tests. It also involves planning, training development, and other activities to help future building operators understand the HVAC system.

The acceptance phase starts with functional tests and verification of all test results. It continues with full documentation: completing the commission report to include records of design changes and all as-built plans and documents, and completing the operations and maintenance manual and system manual. Finally, after system testing and balancing is complete, the owner's operating staff are trained. The acceptance phase ends when "substantial completion" is reached. The warranty period begins from this date.

Table 3 provides information on tasks and participants involved in the GSHP commissioning process. Additional details on this topic, along with preventive maintenance and troubleshooting information, are included in Caneta (2001).

GROUND-COUPLED HEAT PUMPS

Vertical Design

In the design of vertical GCHPs, accurate knowledge of soil/rock formation thermal properties is critical. These properties can be estimated in the field by installing a loop of approximately the same size and depth as the heat exchangers planned for the site. Heat is added in a water loop at a constant rate and data are collected as shown in Figure 14. Inverse methods are applied to find thermal conductivity, diffusivity, and temperature of the formation. These
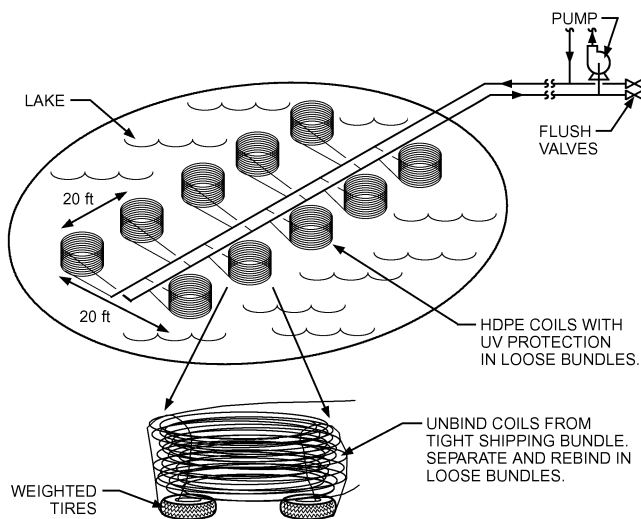
Fig. 13   Lake Loop Piping

Table 3 Example of GSHP Commissioning Process for Mechanical Design

System	Function	Performed By	Witnessed By
Heat pump piping	Pressure test, clean, and fill	Contractor	A/E
Ground source piping	Pressure test, clean, fill, and purge air	Contractor Contractor	A/E
Pumps	Inspect, test, and start-up	Contractor	—
Heat recovery unit	Inspect, test, and start-up; provide clean set of filters, staff instruction	Manufacturer Contractor Manufacturer	CA — CA/owner
Heat pump units	Inspect, test, and start-up; provide clean filters, staff instruction	Manufacturer Contractor Manufacturer	— — CA/owner
Chemical treatment	Flushing and cleaning, chemical treatment, staff instruction	Contractor Contractor/ manufacturer Manufacturer	A/E and CA — CA/owner
Balancing	Balancing, spot checking, follow-up site visits	TAB contractor TAB contractor TAB contractor	— A/E and CA CA
Controls	Installation/commissioning, staff instruction, performance testing, seasonal testing	Contractor CA CA CA	— CA/owner — —

Source: Caneta (2001).
A/E = Architect/engineer
CA = Commissioning authority
TAB = Testing, adjusting, and balancing

Fig. 14 Thermal Properties Test Apparatus

methods are based on the either the line source (Gehlin 1998; Mogensen 1983; Witte et al. 2002), the cylindrical heat source (Ingersoll and Zobel 1954), or a numerical algorithm (Austin et al. 2000; Shonder and Beck 1999; Spitler et al. 1999). More than one of these methods should be applied, when possible, to enhance reported accuracy. Recommended test specifications are listed in Kavanaugh (2000, 2001) as follows:

• Thermal property tests should be performed for 36 to 48 h.
• Heat rate should be 15 to 25 W per foot of bore, which are the expected peak loads on the U-tubes for an actual heat pump system.

• Standard deviation of input power should be less than ±1.5% of the average value and peaks less than ±10% of average, or resulting temperature variation should be less than ±0.5°F from a straight trend line of a log (time) versus average loop temperature.
• Accuracy of the temperature measurement and recording devices should be ±0.5°F.
• Combined accuracy of the power transducer and recording device should be ±2% of the reading.
• Flow rates should be sufficient to provide a differential loop temperature of 6 to 12°F. This is the temperature differential for an actual heat pump system.
• A waiting period of five days is suggested for low-conductivity soils ($k < 1.0$ Btu/h·ft·°F) after the ground loop has been installed and grouted (or filled) before the thermal conductivity test is initiated. A delay of three days is recommended for higher-conductivity formations ($k > 1.0$ Btu/h·ft·°F).
• The initial ground temperature measurement should be made at the end of the waiting period by direct insertion of a probe inside a liquid-filled ground heat exchanger at three locations, representing the average, or by temperature measurement as the liquid exits the loop during the period immediately after start-up.
• Data collection should be at least once every 10 minutes.
• All aboveground piping should be insulated with a minimum of 0.5 in. closed-cell insulation or equivalent. Test rigs should be enclosed in a sealed cabinet that is insulated with a minimum of 1.0 in. fiberglass insulation or equivalent.
• If retesting a bore is necessary, loop temperature should be allowed to return to within 0.5°F of the pretest initial ground temperature. This typically requires a 10 to 12 day delay in mid- to high-conductivity formations and 14 days in low-conductivity formations if a complete 48 h test has been conducted. Waiting periods can be proportionally reduced if tests were shorter.

The ground-loop design method uses a limited amount of information from commercial systems. A major missing component is long-term, field-monitored data, which are needed to further validate the design method so that the effects of water movement and long-term heat storage are more fully addressed. The conservative designer can assume no benefit from water movement; designers who assume maximum benefit must ignore annual imbalances in heat rejection and absorption.

One design method is based on the solution of the equation for heat transfer from a cylinder buried in the earth. This equation was developed and evaluated by Carslaw and Jaeger (1947) and was suggested by Ingersoll and Zobel (1954) as an appropriate method of sizing ground heat exchangers. Kavanaugh (1985) adjusted the method to account for the U-bend arrangement and hourly heat rate variations. Alternative design methods are described by Eskilson (1987), Morrison (1997), Spitler (2000), and Spitler et al. (2000).

The method of Ingersoll and Zobel (1954) can be used to handle these shorter-term variations. It uses the following steady-state heat transfer equation:

$$q = \frac{L(t_g - t_w)}{R} \qquad (1)$$

where

q = heat transfer rate, Btu/h
L = required bore length, ft
t_g = ground temperature, °F
t_w = liquid temperature, °F
R = effective thermal resistance of the ground, h·ft·°F/Btu

The equation is rearranged to solve for the required bore length L. The steady-state equation is modified to represent the variable heat rate of a ground heat exchanger by using a series of constant-heat-rate "pulses." Thermal resistance of the ground per unit length is calculated as a function of time corresponding to the time span

Table 4   Summary of Potential Completion Methods for Different Geological Regime Types

| Geological Regime Type | Grout | | | Backfill with Cutting | Two-Fill with | |
	0.4 < k ≤ 0.8 Btu/h·ft·°F	0.8 < k ≤ 1.2 Btu/h·ft·°F	k > 1.2 Btu/h·ft·°F		Cuttings Below Aquifers	Other* Below Aquifers
Clay or low-permeability rock,						
no aquifer	—	Yes	Yes	—	Yes	Yes
single-aquifer	—	Yes	Yes	—	—	Yes
multiple-aquifer	Yes	Yes	Yes	Yes	Yes	Yes
Permeable rock,						
no shallow aquifers	—	Yes	Yes	Yes	Yes	Yes
single-aquifer	—	Yes	Yes	Yes	Yes	Yes
multiple-aquifers	—	Yes	Yes	Yes	—	—
Karst terrains with secondary permeability	—	Yes	Yes	Yes	—	—
Fractured terrains with secondary permeability	—	Yes	Yes	Yes	Yes	Yes

*Use of backfill material that has thermal conductivity of $k \geq 1.4$ Btu/h·ft·°F
Yes = Recommended potentially viable backfill methods

over which a particular heat pulse occurs. A term is also included to account for thermal resistance of the pipe wall and interfaces between the pipe and fluid and the pipe and the ground. The resulting equation takes the following form for cooling:

$$L_c = \frac{q_a R_{ga} + (q_{lc} - 3.41\,W_c)(R_b + \text{PLF}_m R_{gm} + R_{gd} F_{sc})}{t_g - \dfrac{t_{wi} + t_{wo}}{2} - t_p} \quad (2)$$

The required length for heating is

$$L_h = \frac{q_a R_{ga} + (q_{lh} - 3.41\,W_h)(R_b + \text{PLF}_m R_{gm} + R_{gd} F_{sc})}{t_g - \dfrac{t_{wi} + t_{wo}}{2} - t_p} \quad (3)$$

where

F_{sc} = short circuit heat loss factor
L_c = required bore length for cooling, ft
L_h = required bore length for heating, ft
PLF_m = part load factor during design month
q_a = net annual average heat transfer to the ground, Btu/h
q_{lc} = building design cooling block load, Btu/h
q_{lh} = building design heating block load, Btu/h
R_{ga} = effective thermal resistance of ground (annual pulse), h·ft·°F/Btu
R_{gd} = effective thermal resistance of ground (daily pulse), h·ft·°F/Btu
R_{gm} = effective thermal resistance of ground (monthly pulse), h·ft·°F/Btu
R_b = thermal resistance of pipe, h·ft·°F/Btu
t_g = undisturbed ground temperature, °F
t_p = temperature penalty for interference of adjacent bores, °F
t_{wi} = liquid temperature at heat pump inlet, °F
t_{wo} = liquid temperature at heat pump outlet, °F
W_c = power input at design cooling load, W
W_h = power input at design heating load, W

Note: Heat transfer rate, building loads, and temperature penalties are positive for heating and negative for cooling.

Equations (2) and (3) consider three different pulses of heat to account for long-term heat imbalances (q_a), average monthly heat rates during the design month, and maximum heat rates for a short-term period during a design day. This period could be as short as 1 h, but a 4 h block is recommended.

The required bore is the larger of the two lengths L_c and L_h found from Equations (2) and (3). If L_c is larger than L_h, an oversized coil could be beneficial during the heating season. A second option is to install the smaller heating length along with a cooling tower to compensate for the undersized coil. If L_h is larger, the designer should install this length, and during the cooling mode the efficiency benefits of an oversized ground coil could be used to compensate for the higher first cost.

Table 5   Thermal Properties of Selected Soils, Rocks, and Bore Grouts/Fills

	Dry Density, lb/ft³	Conductivity, Btu/h·ft·°F	Diffusivity, ft²/day
Soils			
Heavy clay, 15% water	120	0.8 to 1.1	0.45 to 0.65
5% water	120	0.6 to 0.8	0.5 to 0.65
Light clay, 15% water	80	0.4 to 0.6	0.35 to 0.5
5% water	80	0.3 to 0.5	0.35 to 0.6
Heavy sand, 15% water	120	1.6 to 2.2	0.9 to 1.2
5% water	120	1.2 to 1.9	1.0 to 1.5
Light sand, 15% water	80	0.6 to 1.2	0.5 to 1.0
5% water	80	0.5 to 1.1	0.6 to 1.3
Rocks			
Granite	165	1.3 to 2.1	0.9 to 1.4
Limestone	150 to 175	1.4 to 2.2	0.9 to 1.4
Sandstone		1.2 to 2.0	0.7 to 1.2
Shale, wet	160 to 170	0.8 to 1.4	0.7 to 0.9
dry		0.6 to 1.2	0.6 to 0.8
Grouts/Backfills			
Bentonite (20 to 30% solids)		0.42 to 0.43	
Neat cement (not recommended)		0.40 to 0.45	
20% bentonite/80% SiO₂ sand		0.85 to 0.95	
15% bentonite/85% SiO₂ sand		1.00 to 1.10	
10% bentonite/90% SiO₂ sand		1.20 to 1.40	
30% concrete/70% SiO₂ sand, s. plasticizer		1.20 to 1.40	

Source: Kavanaugh and Rafferty (1997).

Selection of the fill material for the borehole is a function of thermal, regulatory, and economic considerations. Historically, a relatively low-thermal-conductivity bentonite grout commonly used in the water well industry and, in some cases, drill cuttings have been used as fill. More recently, thermally enhanced materials have been developed. Nutter et al. (2001) contains a detailed evaluation of potential fills and grouts for vertical boreholes. Table 5 summarizes potential completion methods for various geological conditions. The term "two-fill" refers to the practice of placing a low-permeability material in the upper portion of the hole and/or in intervals where it is required to separate individual aquifers, and a more thermally advantageous material in the remaining intervals.

Thermal resistance of the ground is calculated from ground properties, pipe dimensions, and operating periods of the representative heat rate pulses. Table 5 lists typical thermal properties for soils and fills for the annular region of the bore holes. Table 6 gives equivalent thermal resistance of the vertical high-density polyethylene (HDPE) U-tubes for two bore hole diameters (d_b).

The most difficult parameters to evaluate in Equations (2) and (3) are the equivalent thermal resistances of the ground. The solutions

Table 6 Thermal Resistance of Bores (R_b) for High-Density Polyethylene U-Tube Vertical Ground Heat Exchangers

U-Tube Diameter, in.	Bore Fill Conductivity,* h·ft·°F/Btu					
	4 in. Diameter Bore			6 in. Diameter Bore		
	0.5	1.0	1.5	0.5	1.0	1.5
3/4	0.19	0.09	0.06	0.23	0.11	0.08
1	0.17	0.08	0.06	0.20	0.10	0.07
1-1/4	0.15	0.08	0.05	0.18	0.09	0.06

*Based on DR 11, HDPE tubing with turbulent flow

Corrections for Other Tubes and Flows		
DR 9 Tubing	Re = 4000	Re = 1500
+0.02 h·ft·°F/Btu	+0.008 h·ft·°F/Btu	+0.025 h·ft·°F/Btu

Sources: Kavanaugh (2001) and Remund and Paul (2000).

of Carslaw and Jaeger (1947) require that the time of operation, outside pipe diameter, and thermal diffusivity of the ground be related in the dimensionless Fourier number (Fo):

$$\text{Fo} = \frac{4\alpha_g \tau}{d_b^2} \quad (4)$$

where

α_g = thermal diffusivity of the ground
τ = time of operation
d = outside pipe diameter

The method may be modified to permit calculation of equivalent thermal resistances for varying heat pulses. A system can be modeled by three heat pulses, a 10 year (3650 day) pulse of q_a, a 1 month (30 day) pulse of q_m, and a 6 h (0.25 day) pulse of q_d. Three times are defined as

$$\tau_1 = 3650 \text{ days}$$
$$\tau_2 = 3650 + 30 = 3680 \text{ days}$$
$$\tau_f = 3650 + 30 + 0.25 = 3680.25 \text{ days}$$

The Fourier number is then computed with the following values:

$$\text{Fo}_f = 4\alpha\tau_f/d_b^2$$
$$\text{Fo}_1 = 4\alpha(\tau_f - \tau_1)/d_b^2$$
$$\text{Fo}_2 = 4\alpha(\tau_f - \tau_2)/d_b^2$$

An intermediate step in the computation of the thermal resistance of the ground using the methods of Ingersoll and Zobel (1954) is the determination of a G-factor, which is then determined from Figure 15 for each Fourier value.

$$R_{ga} = (G_f - G_1)/k_g \quad (5a)$$

$$R_{gm} = (G_1 - G_2)/k_g \quad (5b)$$

$$R_{gd} = G_2/k_g \quad (5c)$$

Ranges of the ground thermal conductivity k_g are given in Table 6. State geological surveys are a good source of soil and rock data. However, geotechnical site surveys are highly recommended to determine load soil and rock types and drilling conditions.

Performance degrades somewhat because of short-circuiting heat losses between the upward- and downward-flowing legs of a conventional U-bend loop. This degradation can be accounted for by introducing the short-circuit heat loss factor [F_{sc} in Equations (2) and (3)] in the table below. Normally U-tubes are piped in parallel to the supply and return headers. Occasionally, when bore depths

G	Fo
0.128	1
0.263	10
0.433	10^2
0.614	10^3
0.797	10^4
0.978	10^5
1.1595	10^6
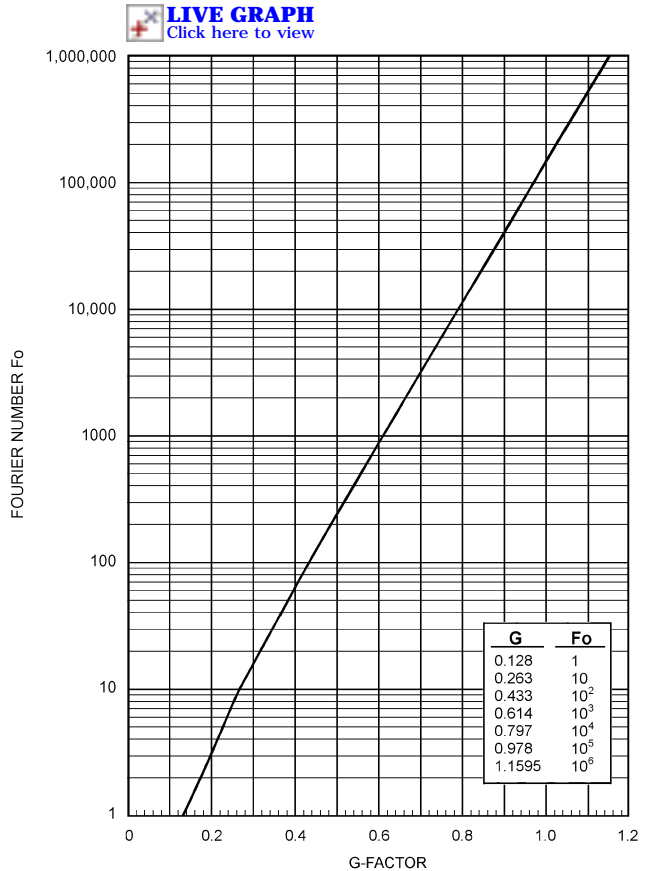
Fig. 15   Fourier/G-Factor Graph for Ground Thermal Resistance
(Kavanaugh and Rafferty 1997)

are shallow, two or three loops can be piped in series. In these cases, short-circuit heat loss is reduced; thus, the values for F_{sc} are smaller than for a single bore piped in series.

Bores per Loop	F_{sc}	
	2 gpm/ton	3 gpm/ton
1	1.06	1.04
2	1.03	1.02
3	1.02	1.01

Temperature. The remaining terms in Equations (2) and (3) are temperatures. The local deep ground temperature t_g can best be obtained from local water well logs and geological surveys. A second, less accurate source is a temperature contour map, similar to Figure 16, prepared by state geological surveys. A third source, which can yield ground temperatures within 4°F, is a map with contours, such as Figure 17. Comparison of Figures 16 and 17 indicates the complex variations that would not be accounted for without detailed contour maps.

Selecting the temperature t_{wi} of water entering the unit is critical in the design process. Choosing a value close to ground temperature results in higher system efficiency, but makes the required ground coil length very long and thus unreasonably expensive. Choosing a value far from t_g allows selection of a small, inexpensive ground coil, but the system's heat pumps will have both greatly reduced capacity during heating and high demand when cooling. Selecting t_{wi} to be 20 to 30°F higher than t_g in cooling and 10 to 20°F lower than t_g in heating is a good compromise between first cost and efficiency in many regions of the United States.

A final temperature to consider is the temperature penalty t_p resulting from thermal interferences from adjacent bores. The designer

must select a reasonable separation distance to minimize required land area without causing large increases in the required bore length (L_c, L_h). Table 7 presents the temperature penalty for a 10 by 10 vertical grid of bores for various operating conditions after 10 years of operation. Correction factors are included to find the permanent temperature change in four other grid patterns. Note that the higher the number of internal bores, the larger the correction factor.

The table includes the length of bore per ton of peak block load to which the temperature change corresponds. Smaller bore lengths

Table 7   Long-Term Change in Ground Field Temperature for 10 by 10 Vertical Grid with 100 Ton Block Load

Equivalent Full Load Hours Heating/Cooling	Bore Separation, ft	Temperature Penalty, °F	Base Bore Length, ft/ton (refrigeration)
1000/500	15	Negligible	180
1000/1000	15	4.7	225
	20	2.4	206
500/1000	15	7.6	260
	20	3.9	228
	15	12.8	345
500/1500	20	6.7	254
	25	3.5	224
	15	Not advisable	
0/2000	20	10.4	316
	25	5.5	252
Correction Factors for Other Grid Patterns			
1 × 10 grid $C_f = 0.36$	2 × 10 grid $C_f = 0.45$	5 × 5 grid $C_f = 0.75$	20 × 20 grid $C_f = 1.14$

Source: Kavanaugh and Rafferty (1997)

Fig. 16   Water and Ground Temperatures (°F) in Alabama at 50 to 150 ft Depth
(Chandler 1987)
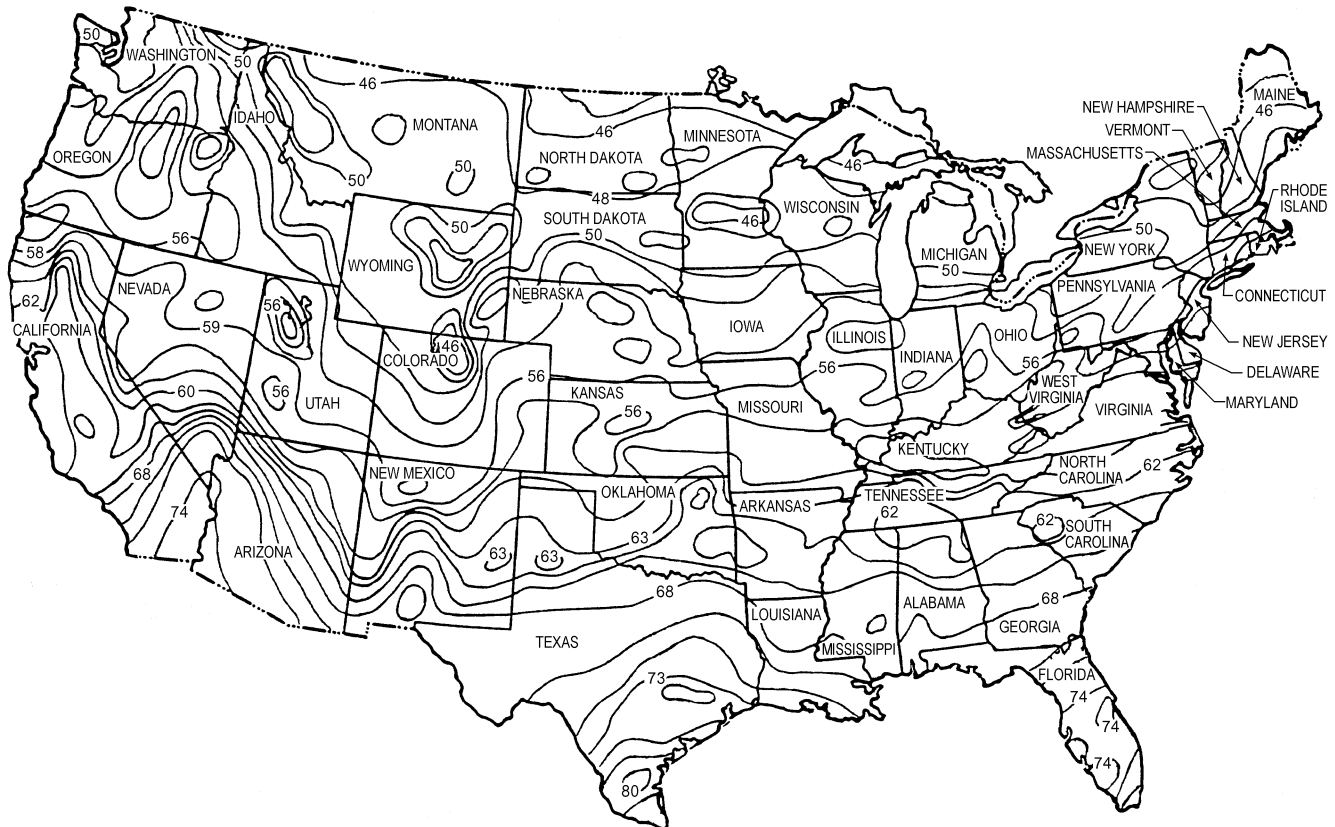
Fig. 17   Approximate Groundwater Temperatures (°F) in the Continental United States

per ton of peak block load result in larger temperature changes; the relationship between bore length and temperature change is inverse and linear.

Values in this table represent worst-case scenarios, and the temperature change is usually mitigated by groundwater recharge (vertical flow), groundwater movement (horizontal flow), and evaporation (and condensation) of water in the soil.

Groundwater movement strongly affects the long-term temperature change in a densely packed ground loop field (Chiasson et al. 2000). Because the effect has not been thoroughly studied, the design engineer must establish a range of design lengths between one based on minimal groundwater movement, as in very tight clay soils with poor percolation rates, and a second based on the higher rates characteristic of porous aquifers.

The long-term temperature change table and a commonly used software for GCHP system design both involve the use of equivalent full-load hour (EFLH) calculations. To the extent that annual loads are proportional to peak loads, the equivalent full-load hours method provides a simple estimate of annual loads from peak loads. The EFLHs in Table 8 provide a quick means to estimate annual loads needed to size ground heat exchangers at the initial feasibility study phase of a project. Because EFLHs vary with both changes in annual loads and changes in peak loads, not all building parameters effects are included in EFLHs. For instance, the building operating hours will change annual loads by increasing the amount of time that internal gains are at elevated levels, but they do not change the peak load. Occupancy hours can add load without increasing the installed capacity, thereby changing the EFLHs. Furthermore, changes in other parameters, such as internal gains, do not necessarily scale with system capacity in the same proportion as annual load, again leading to changing EFLHs. Potential users of EFLHs must understand these sources of variability to use them effectively (Carlson 2001).

Table 8   Equivalent Full-Load Hours (EFLH) for Typical Occupancy with Constant-Temperature Set Points

| | EFLH Occupancy | | | | | | | |
| | School | | Office | | Retail | | Hospital | |
Location	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling
Atlanta, GA	290-200	690-830	690-480	1080-1360	600-380	1380-1860	430-160	2010-2850
Baltimore, MD	460-320	500-610	890-720	690-1080	770-570	880-1480	590-300	1340-2340
Bismarck, ND	500-460	150-250	990-950	250-540	900-810	340-780	730-530	540-1290
Boston, MA	520-450	300-510	1000-960	450-970	870-760	610-1380	680-420	1020-2330
Charleston, WV	440-310	430-570	840-770	620-1140	730-620	820-1600	550-320	1260-2560
Charlotte, NC	320-200	650-730	780-530	1060-1340	670-420	1350-1830	490-180	1990-2820
Chicago, IL	470-390	280-410	920-820	420-780	810-670	550-1090	640-400	870-1780
Dallas, TX	200-120	830-890	520-340	1350-1580	440-280	1660-2090	310-100	2320-3100
Detroit, MI	480-400	230-360	1020-970	390-820	900-790	530-1170	710-460	870-1950
Fairbanks, AK	630-560	26-54	1170-1050	64-200	1090-930	110-320	930-690	210-600
Great Falls, MT	430-360	130-220	890-820	210-490	800-680	290-710	640-420	500-1210
Hilo, HI	1-0	1360-1390	23-13	2440-2580	14-8	2990-3370	0-0	4060-4910
Houston, TX	130-90	940-1000	350-250	1550-1770	300-190	1870-2290	200-70	2540-3320
Indianapolis, IN	480-400	380-560	920-840	560-1000	820-690	730-1410	640-390	1120-2250
Los Angeles, CA	160-80	780-910	580-370	1280-1670	440-250	1740-2350	180-20	2740-3770
Louisville, KY	430-290	550-670	830-710	770-1250	720-570	1000-1720	550-300	1480-2690
Madison, WI	470-390	210-310	900-840	320-640	800-700	420-900	640-440	680-1490
Memphis, TN	240-170	700-830	600-420	1090-1350	510-330	1350-1780	370-140	1910-2680
Miami, FL	12-6	1260-1300	46-34	1980-2150	37-25	2350-2740	12-1	3110-3890
Minneapolis, MN	500-420	200-300	950-860	320-610	860-720	430-870	700-470	680-1420
Montgomery, AL	180-120	840-910	470-330	1260-1510	400-250	1550-1990	260-90	2170-2950
Nashville, TN	320-250	570-740	680-590	830-1280	590-470	1030-1710	450-240	1490-2620
New Orleans, LA	110-67	920-990	320-230	1500-1720	260-160	1820-2240	160-46	2500-3280
New York, NY	440-350	360-550	870-790	540-1040	760-630	720-1480	590-330	1160-2440
Omaha, NE	400-330	310-440	800-720	480-820	720-600	610-1130	570-360	920-1780
Phoenix, AZ	110-65	950-1020	290-210	1340-1610	250-170	1630-2090	140-34	2220-3040
Pittsburgh, PA	500-470	300-530	950-910	440-920	840-750	600-1310	650-420	960-2160
Portland, ME	480-400	190-300	980-880	310-630	870-710	410-900	690-420	700-1520
Richmond, VA	410-270	630-730	820-660	880-1310	710-520	1110-1770	530-250	1650-2760
Sacramento, CA	360-220	680-850	990-640	1080-1430	830-480	1460-2020	540-120	2250-3180
Salt Lake City, UT	540-520	410-710	1060-1040	510-1090	930-830	660-1520	720-440	1060-2470
Seattle, WA	650-460	260-460	1370-1270	440-1200	1170-960	710-1860	850-360	1340-3270
St. Louis, MO	400-280	460-550	800-710	680-1100	700-570	850-1500	550-320	1260-2330
Tampa, FL	58-35	1050-1110	190-140	1800-2000	160-100	2170-2580	90-22	2910-3710
Tulsa, OK	300-240	580-770	620-560	830-1300	540-450	1030-1730	410-220	1470-2630

Notes: 1. The ranges in values are from internal gains at 0.6 and 2.5 W/ft^2.

2. Operating with large temperature setbacks during unoccupied periods (effectively turning off the system) reduces heating EFLHs by 20% and cooling EFLHs by 5%.

Equations relating EFLH to Heating and Cooling Degree Days permitting the calculation of EFLH for locations other than those in Table 8 can be found in Carlson (2001).

Pump and Piping System Options

Loop design can have a substantial effect on both pumping power requirements and system installed cost. A GSHP survey (Caneta 1995) reported that installed pumping power varied from 0.04 to 0.21 hp/ton of heat pump power. This represents 4 to 21% of the total demand of typical GSHP systems and up to 50% of the total energy for some pump control schemes. Kavanaugh et al. (2002) found the total cost of vertical GCHP ground-loop systems (including headers) ranged from $3.00 to $16.60 per ft of vertical bore. The cost of headers is a significant portion of the total and in many cases exceeded the cost of the vertical bore.

In low-rise buildings with large footprints, such as a school, multiple unitary loop systems (Figure 18) are recommended to offset the high cost of central interior piping and ground-loop header costs. Although the total length of vertical bore for unitary systems is greater than for central loop systems, the high cost of interior piping, exterior headers, and valve vaults often offsets the bore cost savings. Additionally, pump demand is substantially reduced in the unitary system because of the short header runs, so low-wattage on/off circulator pumps are suggested.

A compromise in applications with significant load diversity is to group ground loops into multiple smaller subcentral loops in different areas of the building (Figure 19). Subcentral loops can be served by on/off circulator pumps located on each heat pump if a check valve is installed on each heat pump to prevent reverse water circulating through idle units.

Figure 20 is an example of a central loop that can effectively reduce the cost of the required vertical bore in buildings with higher load diversities. The central ground loop consists of several subheader sets each having 6 to 20 vertical U-tube heat exchangers. The subheaders are gathered into a valve manifold located either near the center of the loop field in a below-grade vault or in the building equipment room. Each subheader set has isolation valves for independent purging of air and debris. Interior piping is similar to conventional water-source heat pump systems in which interior piping is routed to individual water-to-air heat pumps in each zone and/or heat pump water heaters and water-to-water heat pumps.

Variable-speed drives (VSDs) are recommended for central loop systems because they offer substantial energy savings compared to primary-secondary pump schemes in GSHP applications. However, in buildings with primary occupancy of less than 60 h per week, measures should be incorporated to turn off the main VSD pump and provide some alternative means of pumping water to critical building zones during low-occupancy or unoccupied periods.

Table 9 demonstrates the results of a component-by-component cost comparison between a central GCHP loop and a set of eight subcentral loops for a 40,000 ft^2, four-story office with a 100 ton cooling load. The single central loop required 20,000 ft of vertical bore and an estimated total piping cost of $211,485. The vertical portion of the subcentral loop cost slightly more, but the total system cost was projected to be lower at $195,722.

Table 10 is a similar comparison between a central loop and multiple unitary loop for a 57,000 ft^2 elementary school. The projected 17% reduction in cost (from $379,570 to $314,909) of the unitary system is more significant compared to the reduction in the four-story office because of the layout of the building. The single-story large-footprint design increases the cost of a central loop because of the long interior piping runs, even though the vertical portion of the central loop system was smaller. The unitary loop system benefits because the large footprint provides ample space for loops to be located near the heat pump units.

Horizontal and Small Vertical System Design

The buried pipe of a closed-loop GSHP may theoretically produce a change in temperature in the ground up to 16 ft away. For all
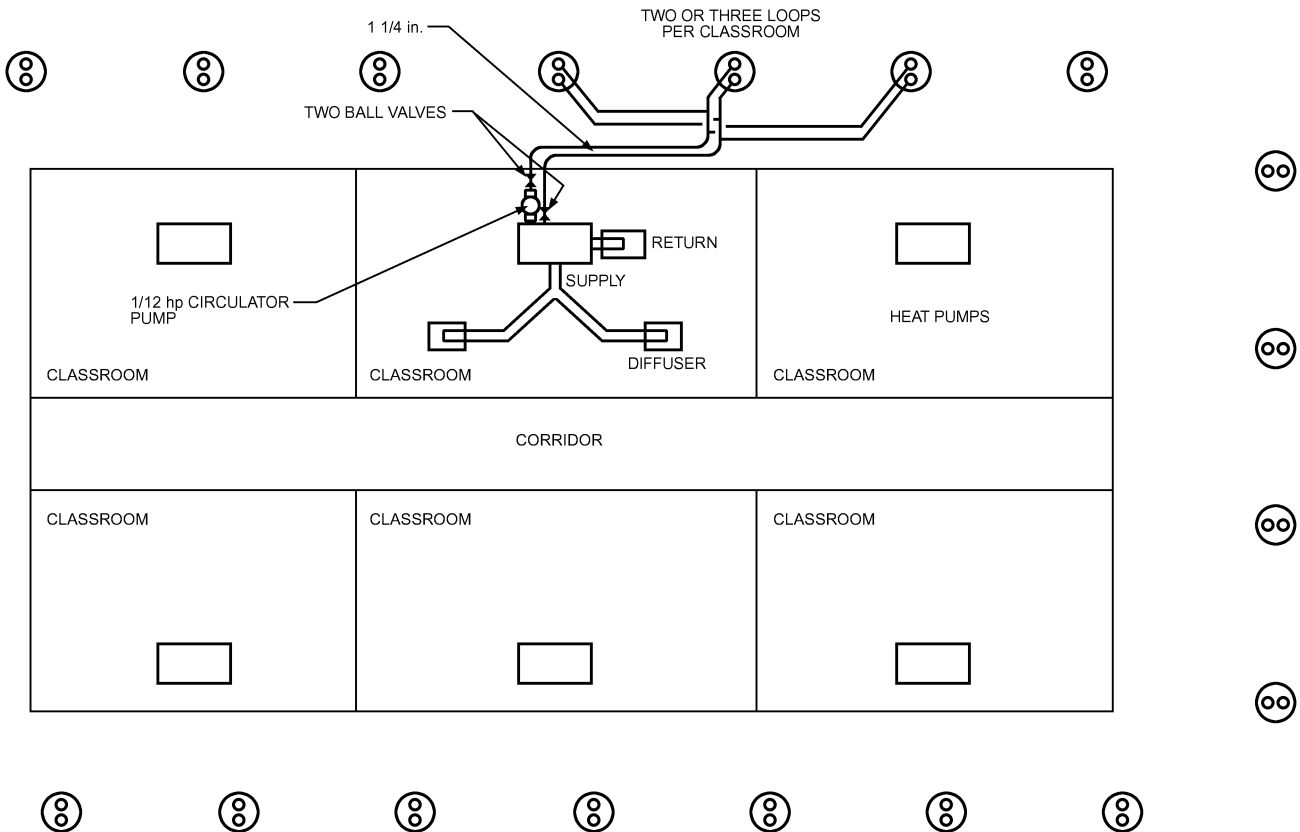
Fig. 18   Unitary GCHP Loops with On/Off Circulator Pumps
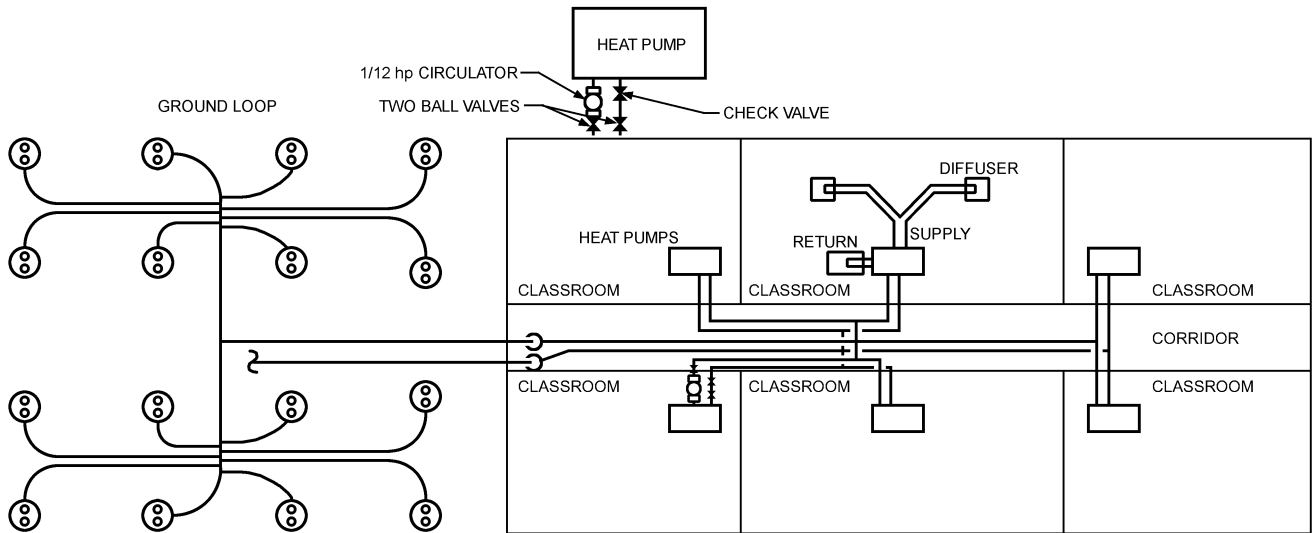
Fig. 19   Subcentral GCHP Loop with On/Off Circulator Pumps
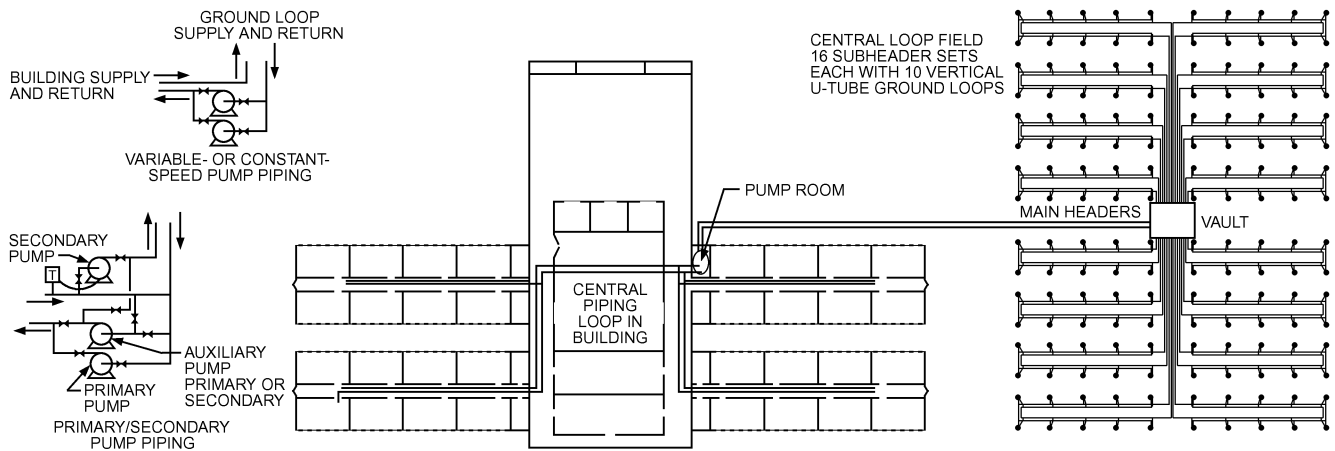
Fig. 20   Central Loop GCHP

Table 9   GCHP Piping Cost Comparison for Four-Story Office

Section	Central Loop	Subcentral Loops	
		Single Loop	Building
Header piping	$ 6,385	$526	$ 4,382
Close headers	0	352	2,932
Excavation/fill	2,493	227	1,891
Vaults	13,069	0	0
Interior pipe	20,427	2,968	24,873
Interior fittings	9,603	802	6,681
Penetrations	440	234	1,949
Interior pipe installation	9,402	519	4,323
Unit connections	16,986	2,328	14,411
Vertical loop	132,680	16,120	134,280
	$211,485		**$195,722**
Vertical loop cost	$6.63/ft		$6.63/ft
Total loop cost	$10.57/ft		$9.67/ft
Vertical loop cost	$1,327/ton		$1,343/ton
Total loop cost	$2,114/ton		$1,956/ton

Table 10   GCHP Piping Cost Comparison for School

Section	Central Loop, 120 Bores @ 245 ft	Unitary Loops, 132 Bores @ 245 ft	
		Single Loop	Building
Header piping	$ 22,655	$85	$ 3,744
Close headers	0	117	5,134
Excavation/fill	4,053	80	3,520
Vaults	14,858	0	0
Interior pipe	66,442	1230	54,120
Interior fittings	17,252	113	4,979
Penetrations	440	234	10,296
Interior pipe installation	32,175	60	2,644
Unit connections	26,664	362	15,928
Vertical loop	195,039	4876	214,544
	$379,570		**$314,909**
Vertical loop cost	$6.63/ft		$6.63/ft
Total loop cost	$12.91/ft		$10.71/ft
Vertical loop cost	$1,300/ton		$1,430/ton
Total loop cost	$2,530/ton		$2,099/ton
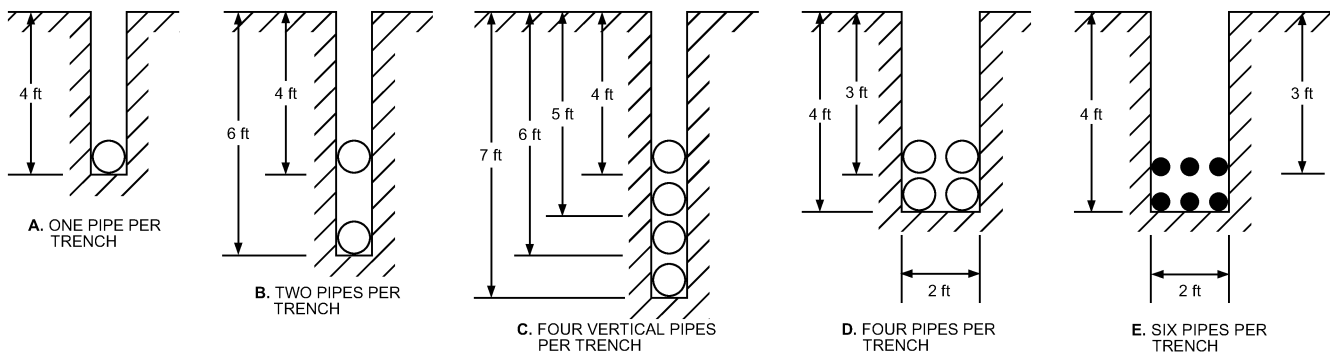
Fig. 21   Horizontal Ground Loop Configurations

practical purposes, however, the ground temperature is essentially unchanged beyond about 3 ft from the pipe loop. For that reason, the pipe can be buried relatively near the ground surface and still benefit from the moderating temperatures that the earth provides. Because the ground temperature may fluctuate as much as ±10°F at a depth of 6 ft, an antifreeze solution must be used in most heating-dominated regions. The critical design aspect of horizontal applications is to have enough buried pipe loop within the available land area to serve the equipment. The design guidelines for residential horizontal loop installations can be found in OSU (1988b).

A horizontal loop design has several advantages over a vertical loop design for a closed-loop ground source system:

- Installation of the ground loop is usually less expensive than for vertical well designs because the capital cost of a backhoe or trencher is only a fraction of the cost of most drilling rigs.
- Most ground-source contractors must have a backhoe for construction of the header pits and trenches to the building, so they can perform the entire job without the need to schedule a special contractor.
- Large drilling rigs may not be able to get to all locations because of their size and weight.
- There is usually no potential for aquifer contamination because of the shallow depth of the trench.
- There is minimal residual temperature effect from unbalanced annual loads on the ground loop because the heat transfer to or from the ground loop is small compared to the normal heat transfer occurring at the ground surface.

Some limitations on selecting a horizontal loop design include the following:

- The minimum land area needed for most nonspiral horizontal loop designs for an average house is about 0.5 acre. Horizontal systems are not feasible for most urban houses, which are commonly built on smaller lots.
- The larger length of pipe buried relatively near the surface is more susceptible to being cut during excavations for other utilities.
- Soil moisture content must be properly accounted for in computing the required ground loop length, especially in sandy soils or on hilltops that may dry out in summer.
- Rocks and other obstructions near the surface may make excavation with a backhoe or trencher impractical.

Multiple pipes are often placed in a single trench to reduce the land area needed for horizontal loop applications. Some common multiple pipe arrangements are shown in Figure 21. When pipes are placed at two depths, the bottom row is placed first, and then the trench is partially backfilled before the upper row is put in place. Rarely are more than two layers of pipe used in a single trench because of the extra time needed for the partial backfilling. Higher pipe densities in the trench provide diminishing returns because
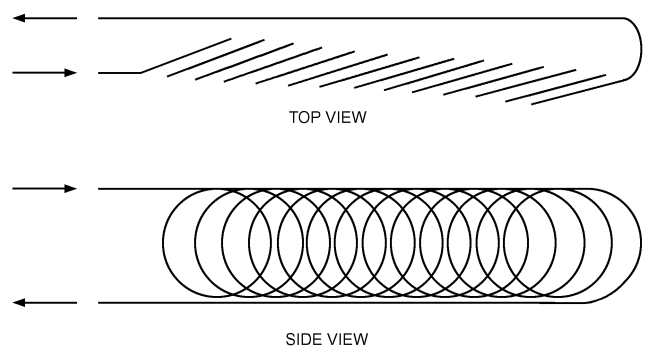
Fig. 22   General Layout of Spiral Earth Coil

thermal interference between multiple pipes reduces the heat transfer effectiveness of each pipe. The most common multiple-pipe applications are the two-pipe arrangement used with chain trenchers and the four- or six-pipe arrangements placed in trenches made with a wide backhoe bucket.

An overlapping spiral configuration, shown in Figure 22, has also been used with some success. However, it requires special attention during backfilling to ensure that soil fills all the pockets formed by the overlapping pipe. Large quantities of water must be added to compact the soil around the overlapping pipes. The backfilling must be performed in stages to guarantee complete filling around the pipes and good soil contact. The high pipe density (up to 10 ft of pipe per linear foot of trench) may cause problems in prolonged extreme weather conditions, either from soil drying during cooling or from freezing during heating. This spiral design has been used in vertical trenches cut with a chain trencher as well as in laying the coil flat on the bottom of a large pit excavated with a bulldozer. Installations using the horizontal spiral coil on the bottom of a pit have generally performed better than those with spiral coils that were stood upright in a vertical trench.

The extra time needed to backfill and the extra pipe length required make spiral configurations nearly as expensive to install as straight pipe configurations. However, the reduced land area needed for the more compact design may allow use on smaller residential lots that would be too small for conventional horizontal-pipe ground-loop designs. The spiral pipe configuration laid flat in a horizontal pit arrangement is used commonly in the northern Midwest part of the United States, where sandy soil causes vertical trenches to collapse. A large open pit is excavated by a bulldozer, and then the overlapping pipes laid flat on the bottom of the pit. The bulldozer is also used to cover the pipe, being careful to not run over them with the bulldozer tread.

Although most horizontal closed-loop systems are installed with either a chain trencher or a backhoe, horizontal boring machines are also now available for this application. Developed

for buried utility applications such as electric or potable water service, these devices simply bore through the ground parallel to the ground surface. A detector at the surface can show the exact point where the boring head is located underground so that the boring process does not penetrate other known utilities or cross over into a neighbor's lot.

Most horizontal loop installations place the pipe loops in a parallel rather than a single (series) loop to reduce pumping power (Figure 23). Parallel loops may require slightly more pipe, but may use smaller pipe and thus have smaller internal volumes requiring less antifreeze (if needed). Also, the smaller pipe is typically much less expensive for a given length, so total pipe cost should be less
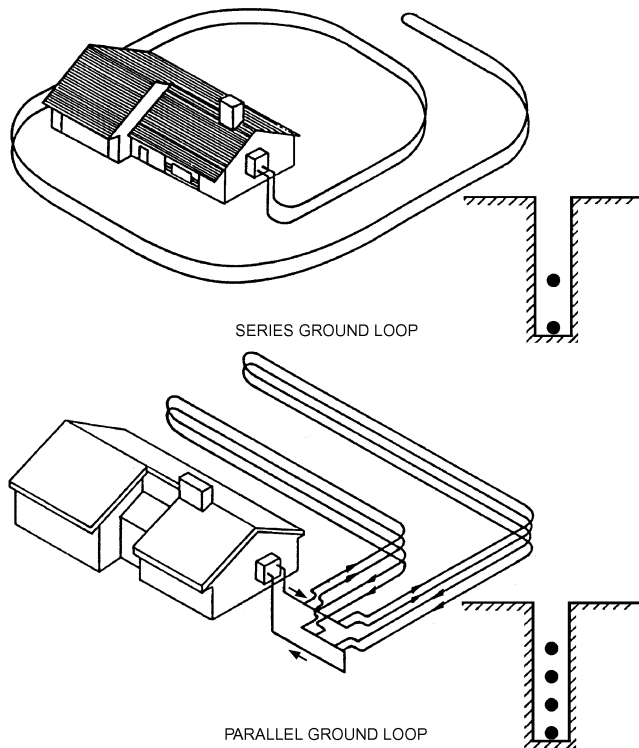
Fig. 23   Parallel and Series Ground Loop Configurations

for parallel loops. An added benefit is that parallel loops can be flushed out with a smaller purge pump than would be required for a larger single-pipe loop. A disadvantage of parallel loops is the potential for unequal flow in the loops and thus nonuniform heat exchange efficiency.

The time required to install a horizontal loop is not much different from that for a vertical system. For the arrangements described, a two-person crew can typically install the ground loop for an average house in a single day.

Soil characteristics are an important concern for any ground loop design. With horizontal loops, the soil type can be more easily determined because the excavated soil can be inspected and tested. EPRI (1990) compiled a list of criteria and simple test procedures that can be used to classify soil and rock for horizontal ground-loop design.

Although soil type and moisture content are important considerations in sizing the ground loop, some design guidelines have been developed based on extensive analysis of monitored systems in mostly southern climates (Kavanaugh and Calvert 1995). Table 11 gives recommended trench lengths for the various types of commonly used excavation methods. Heating-mode run times approaching 100% on a daily basis would be the norm at heating design conditions in heating-dominated climates. In contrast, daily run times of no more than 50% would be encountered at design cooling conditions in cooling-dominated climates. The combination of long run times and ice formation around the pipes makes performance of horizontal systems dependent on both the loop field design and how the system is matched to the building load. Though many thousands of these systems have been installed in heating climates, no comparable analysis has been performed to determine proper design guidelines. The loop length data in Table 11 for soil temperatures below 56°F are based on nominal heat pump capacity and use of supplemental resistance heat at design conditions. If installing such a system for the first time, contact several experienced contractors in the area to determine successful design lengths for the local climate and soil types.

Additional considerations for horizontal loop systems in colder climates arise from the potential for ice formation around the pipe loop. The loop should not pass within 2 ft of any buried water line (potable, sewer, or rainwater). If such proximity cannot be avoided, the GCHP loop can be insulated in that area. Horizontal loops should not be placed closer than 6 ft from a basement or crawl space wall when buried parallel to the wall. Heaving from ice formation could cause structural damage if placed in close proximity to the wall.

Table 11   Recommended Lengths of Trench or Bore per Ton for Residential GCHPs

Coil Type[a]		Pitch[b]	Ground Temperature, °F						
		Feet of Pipe per Feet Trench/Bore	44 to 47	48 to 51	52 to 55	56 to 59	60 to 63	64 to 67	68 to 70
Horizontal	10-Pitch Spiral	10	125	120	115	120	125	150	180
	6-Pipe/6-Pitch Spiral	6	180	160	150	160	180	200	230
	4-Pipe/4-Pitch Spiral	4	190	180	170	180	190	220	260
	2-Pipe	2	300	280	250	280	300	340	400
Vertical U-tube	3/4 in. Pipe	2	180	170	155	170	180	200	230
	1 in. Pipe	2	170	160	150	160	170	190	215
	1 1/4 in. Pipe	2	160	150	145	150	160	175	200

Source: Kavanaugh and Calvert (1995).
[a]Lengths based on DR11 high-density polyethylene (HDPE) pipe. See Figures 21 to 23 for details.
[b]Multiply length of trench by pitch to find required length of pipe.

Note: Based on $k = 0.6$ Btu/h·ft·°F for horizontal loops and $k = 1.2$ Btu/h·ft·°F for vertical loops. Figures for soil temperatures < 56°F based on modeling using nominal heat pump capacity and assumption of auxiliary heat at design conditions.

Multiply Table 11 Values by Bold Values Below to Correct for Other Values of Ground Conductivity

	Ground Thermal Conductivity in Btu/h·ft·°F								
	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
Horizontal loop	1.22	1.0	0.89	0.82	—	—	—	—	—
Vertical loop*	—	—	1.23	1.10	1.0	0.93	0.87	0.83	0.79

*Vertical loop values based on an annular fill with $k = 0.85$ Btu/h·ft·°F. Multiply lengths by 1.2 for $k_{annulus} = 0.4$ Btu/h·ft·°F and 0.95 for $k_{annulus} = 1.1$ Btu/h·ft·°F.

Table 12   Recommended Residential GCHP Piping Arrangements and Pumps

	Nominal Heat Pump Capacity, tons				
	2	**3**	**4**	**5**	**6**
	Required Flow Rate, gpm				
	5 to 6	**7 1/2 to 9**	**10 to 12**	**12 to 15**	**15 to 18**
Coil Type*	Number of Parallel Loops				
Spiral (10 pt.)	3 to 4	4 to 6	6 to 9	8 to 10	8 to 10
6-Pipe	3 to 4	4 to 6	6 to 9	8 to 10	8 to 10
4-Pipe	2 to 3	4 to 6	5 to 8	6 to 9	6 to 10
2-Pipe	2 to 4	3 to 5	4 to 6	5 to 8	6 to 10
Vertical 3/4 in. pipe	2 to 3	3 to 5	4 to 6	5 to 8	6 to 10
1 in. pipe	2 to 3	2 to 4	3 to 5	4 to 6	4 to 6
1 1/4 in. pipe	1 to 2	1 to 2	2 to 3	2 to 3	2 to 4
Trench Length	Header Diameter (PE Pipe), in.				
Less than 100 ft	1 1/4	1 1/4	1 1/2	1 1/2 to 2	1 1/2 to 2
100 to 200 ft	1 1/4	1 1/2	1 1/2	2	2
	Size (No.) of Pumps Required				
	1/12 hp (1)	1/6 hp (1)	1/12 hp (2)	1/6 hp (2)	1/6 hp (2)

Source: Kavanaugh and Calvert (1995).
*Based on DR11 HDPE pipe.

Leaks in the heat-fused plastic pipe are rare when attention is paid to pipe cleanliness and proper fusion techniques. Should a leak occur, it is usually best to try to isolate the leaking parallel loop and abandon it in place. The effort required to find the source of the leak usually far outweighs the cost of replacing the defective loop. Because the loss of as little as 0.25 gal of water from the system causes the system to lose pressure and shut down, leaks cannot be located by looking for wet soil, as is commonly done with water lines.

Although leaks should be rare with properly thermally fused pipe, some states have adopted restrictions against the use of certain types of antifreeze mixtures in GCHP systems; check local water-quality regulations before selecting a mixture. Methanol has been used extensively because of its low cost and good physical properties when cold. Comprehensive studies by Heinonen and Tapscott (1996) and Heinonen et al. (1997) showed that propylene glycol is a good alternative when issues of flammability or environmental safety are important considerations. A more thorough discussion of antifreeze solutions is given in the Antifreeze Requirements section of this chapter.

Fluid Flow and Loop Circuiting

Residential systems, like commercial applications, sometimes have excessive pumping power. This trend may result from under-sized piping, excessive amounts of viscous antifreeze solutions, or conservative pump sizing. Because a 3 ton heat pump with an energy efficiency ratio (EER) of 15 requires a total power (compressor and fan) of 2400 W, the addition of a second 1/6 hp pump (which draws 245 W) reduces system efficiency by 10%. Table 12 provides as a guideline to ensure adequate liquid flow rate with the least possible number of pumps. The table is to be used in conjunction with Table 11 and applies to loops with 0 to 15% propylene glycol solutions (by volume). This solution has the reputation of being the most difficult of the commonly used solutions to pump when cold. However, it is no more difficult to pump than ethyl alcohol, and pumping penalties can be mitigated by adding only the required amount of antifreeze. Shorter loops may require higher levels of antifreeze solutions. See the section on Antifreeze Requirements for more details. Any exposed piping above the frost line must be insulated with closed-cell insulation with ultraviolet (UV) protection (paint or wrap).

Residential Design Example

Design the vertical ground coupling grid and the pumping loop for a 4 ton (48,000 Btu/h) heat pump system. The home is located in

**EXAMPLE
4 TON VERTICAL
GCHP SYSTEM**

(LENGTHS VARY; SEE TABLE FOR OTHER APPLICATIONS AND CLIMATES DESIGN)

WATER-TO-AIR HEAT PUMP
• EXTENDED RANGE (EWT = 25 to 105°F)
• HIGH EFFICIENCY (ARI *STANDARD* 300 EER = 13+)

PUMP
THREE-WAY PURGE VALVES
P/T TAP
1 1/2 in. HDPE HEADERS
CLOSE HEADER
1 in. DR11 HDPE U-TUBES
15 to 20 ft MINIMUM
165 ft
FOUR CIRCUITS, FOUR BORES
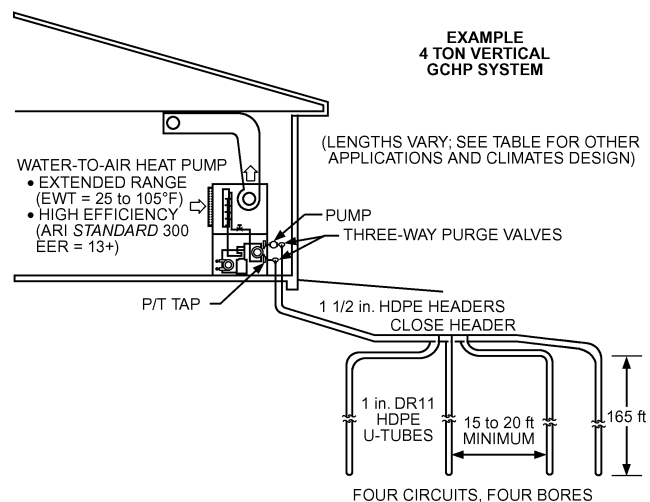
Fig. 24   Residential Design Example

Nashville, Tennessee, and the header pipes can be brought into the equipment room where the unit will be located. The driller can bore 4.5 in. holes to a depth of 175 ft in the light limestone and clay at the site. The owner wants the drilling site to be located 75 ft from the house. Thermally enhanced grout with thermal conductivity of 0.85 Btu/h·ft·°F is used to fill the annular region between the U-tubes and borehole walls.

Solution:

The soil temperature is estimated to be 59°F in Nashville (see Figure 17). Table 11 suggests bore lengths of 170 ft/ton for 3/4 in. U-bends, 160 ft/ton for 1 in., and 150 ft/ton for 1 1/4 in. (bores are deep, greater than 100 ft). However, 1 1/4 in. U-bends are very difficult to install into a 4.5 in. bore hole, and are not considered. Therefore, either 680 ft (170 ft/ton × 4 tons) of 3/4 in. U-bend coupling or 640 ft (160 × 4 tons) of 1 in. coupling is required. The latter is used in this example. Also, Table 11 is based on a soil conductivity of 1.2 Btu/h·ft·°F, which is an approximate average between limestone and clay, and a bore fill (or grout) conductivity of 0.85 Btu/h·ft·°F. If the ground conductivity is higher (i.e., more limestone than clay), the loops should be reduced as noted in Table 11; if lower, the loops should be lengthened. Loop lengths also must be lengthened if the bore fill (or grout) conductivity is lower than 0.85 Btu/h·ft·°F, as noted in Table 11.

Layout is dictated by drilling conditions. The total length of 640 ft requires four bores, because the driller can only drill to 175 ft. This can be accomplished with four 160 to 165 ft holes. Table 12 suggests between three and five parallel circuits for the grid. Three and five circuits do not divide evenly into the four U-bends. Therefore, four circuits (one per U-bend) should be used in an arrangement similar to Figure 24.

GROUNDWATER HEAT PUMPS

A groundwater heat pump system (GWHP) removes groundwater from a well and delivers it to a heat pump (or an intermediate heat exchanger) to serve as a heat source or sink. Both unitary or central plant designs are used. In the unitary type, a large number of small water-to-air heat pumps are distributed throughout the building. The central plant design uses one or a small number of large-capacity chillers supplying hot and chilled water to a two- or four-pipe distribution system. The unitary approach is more common and tends to be more energy-efficient.

Direct systems (in which groundwater is pumped directly to the heat pump without an intermediate heat exchanger) are not recommended except on the very smallest installations. Although some systems of this design have been successful, others have had serious difficulty even with groundwater of apparently benign chemistry. Thus, prudent design for commercial/industrial-scale projects isolates groundwater from the building system with a heat exchanger. The increased capital cost of installing the heat exchanger is only small percentage of the total cost and, in view of these systems' greatly reduced maintenance requirements, is quickly recovered.

Regardless of the type of equipment installed in the building, the specific components for handling groundwater are similar. Primary items include (1) wells (supply and, if required, injection), (2) well pump, and (3) groundwater heat exchanger. Some specifics of these items are discussed in the section on Direct-Use Systems. In addition to those comments, the following considerations apply specifically to unitary GWHP systems using a groundwater isolation heat exchanger.

Design Strategy

An open-loop system design must balance well pumping power with heat pump performance. As groundwater flow increases through a system, more favorable average temperatures are produced for the heat pumps. Higher flow rates, to a point, increase system EER or COP as increased well pump power is outweighed by decreased heat pump power requirements (because of the more favorable temperatures). At some point, additional increases in groundwater flow result in a greater increase in well pump power than the resulting decrease in heat pump power. The key strategy in open-loop system design is identifying the point of maximum system performance with respect to heat pump and well pump power

requirements. Once this optimum relationship has been established for the design condition, the method of controlling the well pump determines the extent to which the relationship is preserved at off-peak conditions. This optimization process involves evaluating the performance of the heat pumps and well pump(s) over a range of groundwater flows. Key data necessary to make this calculation include well performance (flow and drawdown at various groundwater flows) and heat pump performance versus entering water temperatures at different flow rates. Well information is generally derived from well pump test results. Heat pump performance data are available from the manufacturer.

For moderate-efficiency heat pumps (EER of 14.2), efficient loop pump design (7.5 hp/100 tons), and a heat exchanger approach of 3°F, Figure 25 provides curves for two different groundwater temperatures (70 and 50°F) and two well pump heads (100 and 300 ft). The curves are plotted for constant well pump head, a situation which does not occur in practice. In reality, well pump head rises with flow but at a rate typically less than that in friction head applications.

Although the four curves show a clear optimum flow, sometimes operating at a lower groundwater flow reduces well/pump capital cost and the problem of fluid disposal. These considerations are highly project specific, but do afford the designer some latitude in flow selection. Generally, an optimum design results in a groundwater flow rate that is less than the building loop flow rate.

Table 13 provides design data for a specific example system.
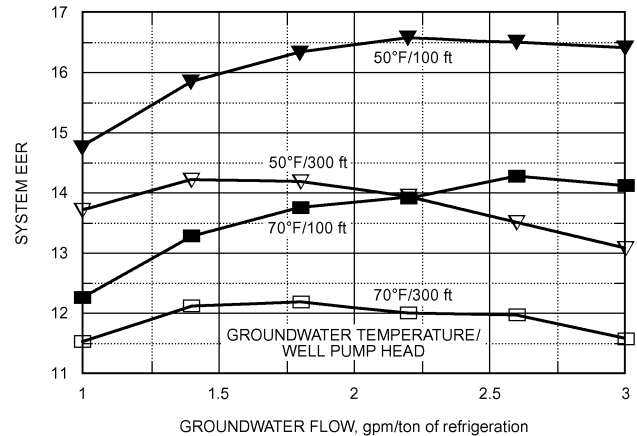
Fig. 25   Optimum Groundwater Flow for Maximum System EER
(Kavanaugh and Rafferty 1997)

Table 13   Example GWHP System* Design Data

Heat Pump EWT, °F	Heat Pump LWT, °F	Heat Pump EER	Ground Water LWT, °F	Ground Water Flow, gpm	Well Pump Head, ft	Well Pump kW	Loop Pump kW	System EER
61.0	72.4	17.6	68.4	289	256	23.7	4.8	11.8
63.0	74.5	17.3	70.5	233	229	17.5	4.8	12.5
65.0	76.5	16.9	72.5	196	210	13.7	4.8	12.9
67.0	78.6	16.5	74.6	169	197	11.4	4.8	13.0
69.0	80.6	16.1	76.6	149	186	9.7	4.8	13.1
71.0	82.7	15.7	78.7	133	179	8.5	4.8	13.0
73.0	84.7	15.3	80.7	120	172	7.5	4.8	12.9
75.0	86.7	15.1	82.7	110	167	6.7	4.8	12.9
77.0	88.8	14.9	84.8	101	163	6.0	4.8	12.8
79.0	90.8	14.6	86.8	94	159	5.5	4.8	12.6
81.0	92.3	14.2	88.9	88	156	5.1	4.8	12.4
83.0	94.9	13.4	90.9	82	153	4.7	4.8	12.2

*Block cooling load 85 tons, 60°F groundwater, 75 ft well static water level, 2 gpm/ft specific capacity, 37 ft surface head losses, 4°F heat exchanger approach, 213 gpm building loop flow at 65 ft head.

WATER WELLS

This section includes information on water wells that is generally common to both direct-use and groundwater heat pump (GWHP) systems.

An **aquifer** is a geologic unit that is capable of yielding groundwater to a well in sufficient quantities to be of practical use (UOP 1975). Aquifers can exist in areas where water is present along with pore spaces in the subsurface materials sufficient to allow the water to move laterally.

In many projects, construction of the well (or wells) is handled through a separate contract between the owner and the driller. As a result, the engineer is not responsible for its design. However, because design of the building system depends on well performance, it is critical that the engineer be familiar with well terminology and test data. The most important consideration with regard to the wells is that they be completed and tested (for flow volume and water quality) before final system design if possible.

Figure 26 illustrates some of the more important well terms. Several references (Anderson 1984; Campbell and Lehr 1973; EPA 1975; Roscoe Moss Company 1985) cover well drilling and well construction in detail.

Static water level (SWL) is the level that exists under static (nonpumping) conditions. In some cases, this level is much closer to the surface than that at which the driller encounters water during drilling. **Pumping water level (PWL)** is the level that exists under specific pumping conditions. Generally, this level is different for different pumping rates (higher pumping rates mean lower pumping levels). The difference between the SWL and the PWL is the **drawdown**. The **specific capacity** of a well is frequently quoted in gpm per foot of drawdown. For example, for a well with a static level of 50 ft that produces 150 gpm at a pumping level of 95 ft, drawdown = 95 − 50 = 45 ft; specific capacity = 150/45 = 3.33 gpm per foot.

Water entrance velocity (through the screen or perforated casing) can be an important design consideration. Velocity should be limited to a maximum of 0.1 fps to avoid incrustation of the entrance openings. The **pump bowl assembly** (impeller housings and impellers) is always placed sufficiently below the expected pumping level to prevent cavitation at the peak production rate. For the previous example, this pump should be placed at least 115 ft below the casing top (pump setting depth = 115 ft) to allow for adequate submergence at peak flow. The specific **net positive suction head (NPSH)** required for a pump varies with each application and should be carefully considered in selecting the setting depth.
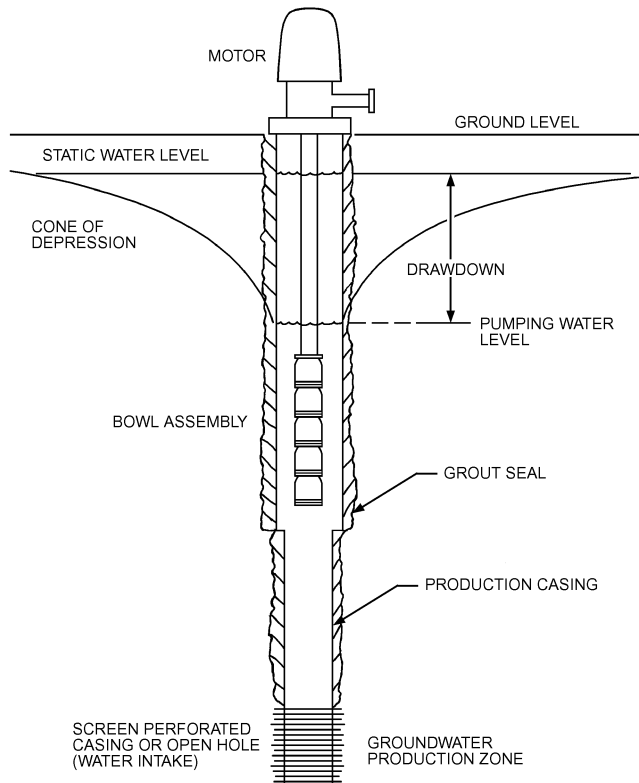
For the well pump, **total pump head** is composed of four primary components: lift, column friction, surface requirements, and injection head. **Lift** is the vertical distance that water must be pumped to reach the surface. In the example, lift is 95 ft. The additional 20 ft of submergence imposes no static pump head.

Column friction, the friction loss in the pump column between the bowl assembly and the surface, is calculated from pump manufacturer data in a similar manner to other pipe friction calculations (see Chapter 36 of the 2005 *ASHRAE Handbook—Fundamentals*). **Surface pressure requirements** account for friction losses through piping, and heat exchangers and controls. **Injection pressure requirements** are a function of well design, aquifer conditions, and water quality. In theory, an injection well penetrating the same aquifer as the production well experiences a water level rise (assuming equal flows) that mirrors the drawdown in the production well. Using the earlier example, an injection well with a 50 ft static level would experience a water level rise of 45 ft, resulting in a surface injection pressure of 45 − 50 = −5 ft (i.e., a water level that remains 5 ft below the ground surface). Thus, no additional pump pressure is required for injection in the example.

In practice, injection pressure requirements usually exceed the theoretical value. With good (nonscaling) water, careful drilling, and little sand production, injection pressure should be near the theoretical value. For poor water quality, high sand production, or poor well construction, injection pressure may be 30 to 60% higher.

The well casing diameter depends on the diameter of the pump (bowl assembly) necessary to produce the required flow rate. Table 14 presents nominal casing sizes for a range of water flow rates.

In addition to the production well, most systems should include an injection well to dispose of the fluid after it has passed through the system. Injection stabilizes the aquifer from which the fluid is withdrawn by reducing or eliminating long-term drawdowns, and helps to ensure long-term productivity. Construction of injection wells differs from production wells primarily in the recommended screen velocity (0.05 ft/sec, or 1/2 that of production wells) and well sealing design. Injection wells, particularly those likely to be subject to positive injection pressure, should be fully sealed from the top of the injection zone to the surface.

Flow Testing

When possible, well testing should be completed before mechanical design. Only with actual flow test data and water chemical analysis information can accurate design proceed.

Flow testing can be divided into three different types of tests: rig, short-term, and long-term (Stiger et al. 1989). Rig tests are

Fig. 26   Water Well Terminology

Table 14   Nominal Well Surface Casing Sizes

Pump Bowl Diameter, in.	Suggested Casing Size, in.	Minimum Casing Size, in.	Submersible Flow Range (3450 rpm), gpm	Lineshaft Flow Range (1750 rpm), gpm
4	6	5	<80	<50
6	10	8	80 to 350	50 to 175
7	12	10	250 to 600	150 to 275
8	12	10	360 to 800	250 to 500
9	14	12	475 to 850	275 to 550
10	14	12		500 to 1000
12	16	14		900 to 1300

generally very short and are accomplished while the drilling rig is on site. The primary purpose of this test is to purge the well of remaining drilling fluids and cuttings and to get a preliminary indication of yield. The length of the test is generally governed by the time required for the water to run clean. The rate is determined by the available pumping equipment. Frequently, the well is "blown" or pumped with the drilling rig's air compressor. As a result, little can be learned about the well's production characteristics from a rig test. If the well is air lifted, it may not be useful to collect water samples for chemical analysis because certain chemical constituents may be oxidized by the compressed air.

Properly conducted, short-term, single-well tests lasting 4 to 24 h yield information about well flow rate, temperature, drawdown, and recovery. These tests are used most frequently for direct-use and GWHP applications. The test is generally run with a temporary electric submersible pump or lineshaft turbine pump driven by an internal combustion engine and are often performed by a well pump contractor.

A step test, the most common type, involves at least three production rates, the largest being equal to the design flow rate for the system served. The three points are the minimum required to determine a productivity curve for the well that relates production to drawdown (Stiger et al. 1989). The key parameters monitored during these tests are well water level and water flow. Water level and pumping rate should be stabilized at each point before the flow is increased. In most cases, water level is monitored with a "bubbler" or an electric sounder, and flow is measured using an orifice meter. This short-term test is generally used for small projects and provides information on yield, drawdown, and specific capacity.

Long-term tests of up to 30 days provide information on the reservoir. Normally these tests involve monitoring nearby wells to evaluate interference effects. The data are useful in calculating transmissivity and storage coefficient, reservoir boundaries, and recharge areas (Stiger et al. 1989) but are rarely used for direct-use and GWHP systems.

It is also important to collect background information before the test, and water level recovery data after pumping has ceased. Recovery data in particular can be used to evaluate skin effect, which is a type of well flow resistance caused by residual drilling fluids, insufficient screen or slotted liner area, or improper filter pack.

Groundwater Quality

The importance of groundwater quality depends on the system design. Systems using isolation heat exchangers commonly encounter no water quality issues (other than iron bacteria) that would prevent the application of a GWHP system operating under reasonable maintenance levels.

For systems that use groundwater directly in heat pump units (e.g., standing column systems and small residential GWHP systems), several issues are of concern. The primary water quality problem in the United States is scaling, usually of calcium carbonate (lime). Because this type of scaling is partially temperature driven, the temperature of surfaces that groundwater contacts determines the extent to which scaling will occur. In these systems, peak temperatures in the refrigerant-to-water exchanger in cooling mode are likely to be over 160°F. For the same system using an isolation plate heat exchanger, the groundwater is unlikely to encounter temperatures over 90°F. Using the plate heat exchanger reduces the propensity for scaling and limits any scale that does occur to a single heat exchanger. Rafferty (2000b) provides information on water scaling potential on a state-by-state basis.

Although cupronickel, originally developed for seawater applications, is an excellent material in that role, it provides few benefits for most groundwater applications. It has been shown to perform more poorly than pure copper with hydrogen-sulfide-bearing waters.

Excessive iron, particularly ferrous iron, in the water can result in coating of heat transfer surfaces if the water is exposed to air (allowing the iron to oxidize to the ferric state, a form with much lower solubility in water). Removing this iron from the plates of a single heat exchanger is much less labor-intensive than removing it from tens or hundreds of individual heat pump heat exchangers.

Particulate matter (e.g., sand) in the groundwater stream, although usually not a problem in the mechanical system, can effectively plug injection wells. Sand production should be addressed in construction of the production well (screen/gravel pack/development). If it must be dealt with on the surface, a screen or strainer is preferable to a centrifugal separator. The strainer does not suffer from ineffectiveness at start-up, shutdown, and variable flow as does the centrifugal separator (Kavanaugh and Rafferty 1997).

Well Pumps

Submersible pumps have not performed well in higher-temperature, direct-use projects. However, the submersible pump is a cost-effective option with normal groundwater temperatures, as encountered in heat pump applications. The low temperature eliminates the need to specify an industrial design for the motor/protector, thereby greatly reducing the first cost relative to direct use. Caution should still be used for wells that are expected to produce moderate amounts of sand. The high speed (nominal 3600 rpm) of most submersible pumps makes them susceptible to erosion damage.

Small groundwater systems have frequently been identified with excessive well pump energy consumption. The reasons for excessive pump energy consumption (high water flow rate, coupling to the domestic pressure tank, and low efficiency of small submersible pumps) are generally not present in large, commercial groundwater systems. In large systems, the groundwater flow per unit capacity is frequently less than half that of residential systems. The pressure at the wellhead is not the 30 to 50 psi typical of domestic systems, but is rather a function only of pressure losses through the groundwater loop. Finally, large well pumps have efficiencies of up to 83% compared to the 35 to 40% range for small submersible pumps.

In GWHP system design, the method of control of the well pump determines the extent to which the optimum relationship between well pump power and heat pump power is preserved at off-peak conditions. There are several ways the pump can be controlled. Multiple pumps can be staged to meet system loads, either with multiple wells or with multiple pumps installed in a single well. A dual set-point control similar to that used in boiler/tower systems energizes the well pump above a given temperature in the cooling mode and below a given temperature in the heating mode. Between those temperatures the building loop "floats" without the addition of groundwater. To control well pump cycling, it is necessary to establish a temperature range (difference between pump-on and pump-off temperatures) over which the pump operates in both the heating and cooling modes. The size of this range is primarily a function of the building loop water volume in terms of gallons per peak per ton of peak block system load (Rafferty 2000c). Table 15 summarizes these data. In the example in Table 13, the optimum system building loop return temperature (at peak system EER) is 80.6°F. If this system had a water volume of 8 gal/ton, from Table 15 a range of 8°F in the cooling mode would be required. This range would result in a well pump start temperature of 80.6 + (8/2) = 84.6°F and a well

Table 15 Controller Range Values for Dual Set-Point Well Pump Control*

	Building Loop Thermal Mass in Gallons per Ton of Peak Block Cooling Load						
	2	**4**	**6**	**8**	**10**	**12**	**14**
Cooling Range, °F	31	16	11	8	6	5	4
Heating Range, °F	18	9	6	4	3	3	3

*Table values for pumps > 5 hp. For pumps < 5 hp, three-phase range values may be reduced by 50%.

pump stop temperature of 80.6 − (8/2) = 76.6°F. A similar calculation can be made for the heating mode. It is apparent from Table 15 that, for systems with very low thermal mass, the dual set-point method of control becomes impractical because of the very large temperature range required. For these applications, an alternative method of control (variable speed, staging, etc.) is required.

Heat Exchangers

Design of a plate-and-frame heat exchanger is largely a tradeoff between pressure drop, which influences pumping (operating cost), and overall heat transfer coefficient, which influences surface area (capital cost). In general, exchangers in GWHP systems can be economically selected for approach temperatures (between loop return and groundwater leaving temperatures) as low as 3°F. Most selections involve an approach of between 3 and 7°F and a pressure drop of less than 10 psi on the building loop side. Excessive fouling factors (>0.0002 h·ft^2·°F/Btu) should not be specified when selecting plate heat exchangers, which can be easily disassembled and cleaned.

Heat exchanger cost may be reduced for groundwater applications by using Type 304 stainless steel plates rather than the Type 316 or titanium plates common in direct-use projects. The low temperature and generally low chloride content of heat pump fluids frequently make the less expensive Type 304 material acceptable. Chloride content of the groundwater, particularly in coastal areas, should always be compared to values in Figure 4 to determine plate material acceptability.

Central Plant Systems

Central plant systems, in which a conventional or heat recovery central chiller is connected to a four-pipe system, are the oldest type of open-loop design, having first been installed in the late 1940s. Because of the cost and energy requirements of the central plant design, these systems typically do not result in the same level of energy efficiency as unitary GWHP systems.

For central plant groundwater systems, two heat exchangers are normally used, one in the chilled-water loop and one in the condenser water loop (Figure 27). The evaporator-loop exchanger provides a heat source for heating-dominated operation and the condenser-loop exchanger provides a heat sink for cooling-dominated operation.

Sizing of the **condenser-loop exchanger** is based on providing sufficient capacity to reject the condenser load in the absence of any building heating requirement.

Sizing of the **chilled-water-loop exchanger** must consider two loads. The primary criterion is the load required during heating-dominant operation. The exchanger must transfer sufficient heat (when combined with compressor heat) from the groundwater to the
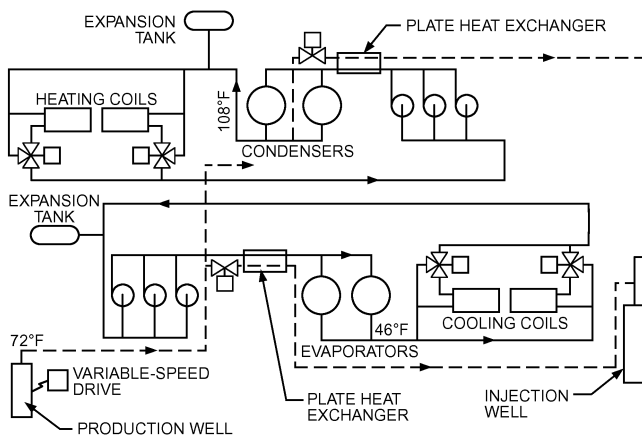
Fig. 27 Central Plant Groundwater System

chilled-water loop to meet the building's space heating requirement. Depending on the relative groundwater and chilled-water temperatures and on the design temperature rise, exchangers may also provide some free cooling during cooling-dominant operation. If groundwater temperature is lower than that of chilled water returning to the exchanger, some chilled-water load can be met by the exchanger. This mode is most likely available in regions with groundwater temperatures below 60°F.

Central plant chiller controls must also allow for the unique operation with a groundwater source. Controls can be similar to those on a heat-recovery chiller with a tower, with one important difference. In a conventional heat-recovery chiller, waste heat is available only when there is a building chilled-water (or conditioning) load. In a groundwater system, a heat source (the groundwater) is available year-round. To take advantage of this source during the heating season, the chiller must be loaded in response to the heating load instead of the chilled-water load. That is, the control must include a heating-dominant mode and a cooling-dominant mode. Two general designs are available for this:

- Chiller capacity remains controlled by chilled-water (supply or return) temperature, and groundwater flow through the chilled-water exchanger is varied in response to the heating load
- Chiller capacity is controlled by the heating-water (condenser) loop temperature, and groundwater flow through the chilled-water exchanger is controlled by chilled-water temperature

For buildings with a significant heating load, the former may be more attractive, whereas the latter may be appropriate for conventional buildings in moderate to warm climates.

Standing-Column Systems

In practice, standing-column wells (SCWs) are a tradeoff between groundwater systems and ground-coupled systems. They do not require well flow testing of the sort necessary for groundwater systems, and conductive heat transfer can be based on existing closed-loop theory. Though standing-column systems have been applied mostly in the northeastern United States, approximately 60% of the country is underlain by near-surface (<150 ft) bedrock suitable for the systems.

A heating capacity of 350,000 to 420,000 Btu/h or cooling capacity of 30 to 35 tons can be expected from a 1500 ft deep standing-column well. Ideal spacing between SCWs is 50 to 75 ft (Orio et al. 2005) Typically, spacing between standing-column wells is greater than vertical closed-loop (GCHP) boreholes. These estimated capacities assume a 10% advective bleed flow, discussed later in this section. Closer spacing affects well field performance and can be evaluated with design software. Additional information on standing-column systems can be found in Spitler (2002).

The standing-column well combines supply and injection wells into one, and does not depend on the presence or flow of groundwater, beyond that of the typical bleed rate of 10 to 20% of total pumped flow. Standing-column wells are always augmented with a bleed circuit, to monitor the entering water temperature. Well water temperatures that are below or above design limits because of variations in rock conductivity, building anomalies, or nonstandard weather patterns can be restabilized (i.e., brought back to far-field temperatures by overflowing smaller amounts of water on command). This advective flow is a powerful short-term method of warming and cooling well columns that are beyond design limits.

Standing-column wells (Figure 28) consist of a borehole cased in steel or other material until competent bedrock is reached. The casing must be driven 25 to 50 ft into and sealed in competent bedrock. Bedrock sealing requirements vary by state. The remaining depth of the well is then self-supporting through bedrock. For deep commercial SCWs, a tail pipe (porter shroud) is inserted to form a conduit to draw up water, and an annulus to return water downward. This tail pipe is perforated at the bottom to form a diffuser.
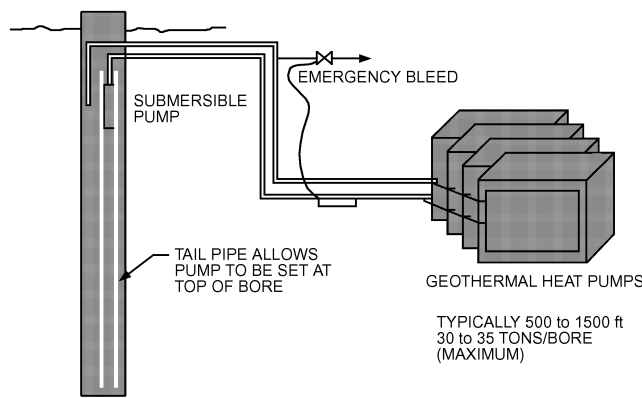
Fig. 28 Commercial Standing-Column Well

Water is drawn into the diffuser and up the central riser pipe to the submersible pump. The well pump must be located below the water table in line with the central riser pipe. The tail pipe allows a shorter, reduced-power wire size as well as more accessible well pump service.

The U.S. Environmental Protection Agency (EPA) Underground Injection Control program considers standing-column reinjection well water a Class V water use, type 5A7, noncontact cooling water for geothermal heating and cooling. The EPA and equivalent state agencies regard SCW reinjection as a beneficial use. Permitting or notice may be required, depending on average daily water flow rates. SCWs are serviced by qualified well contractors with minimal familiarization training.

SURFACE WATER HEAT PUMPS

Surface water bodies can be very good heat sources and sinks if properly used. In some cases, lakes can be the very best water supply for cooling. Various water circulation designs are possible and several of the more common are presented.

In a **closed-loop system**, a water-to-air heat pump is linked to a submerged coil. Heat is exchanged to (cooling mode) or from (heating mode) the lake by the fluid (usually a water/antifreeze mixture) circulating inside the coil. The heat pump transfers heat to or from the air in the building.

In an **open-loop system**, water is pumped from the lake through a heat exchanger and returned to the lake some distance from the point at which it was removed. The pump can be located either slightly above or submerged below the lake water level. For heat pump operation in the heating mode, this type is restricted to warmer climates. Entering lake water temperature must remain above 42°F to prevent freezing.

Thermal stratification of water often keeps large quantities of cold water undisturbed near the bottom of deep lakes. This water is cold enough to adequately cool buildings by simply being circulated through heat exchangers. A heat pump is not needed for cooling, and energy use is substantially reduced. Closed-loop coils may also be used in colder lakes. Heating can be provided by a separate source or with heat pumps in the heating mode. Precooling or supplemental total cooling are also permitted when water temperature is between 50 and 60°F.

Heat Transfer in Lakes

Heat is transferred to lakes by three primary modes: radiant energy from the sun, convective heat transfer from the surrounding air (when the air is warmer than the water), and conduction from the ground. Solar radiation, which can exceed 300 Btu/h per square foot of lake area, is the dominant heating mechanism, but it occurs primarily in the upper portion of the lake unless the lake is very clear. About 40% of solar radiation is absorbed at the surface

(Pezent and Kavanaugh 1990). Approximately 93% of the remaining energy is absorbed at depths visible to the human eye.

Convection transfers heat to the lake when the lake surface is cooler than the air. Wind speed increases the rate at which heat is transferred to the lake, but maximum heat gain by convection is usually only 10 to 20% of maximum solar heat gain. The conduction gain from the ground is even less than convection gain (Pezent and Kavanaugh 1990).

Cooling of lakes is accomplished primarily by evaporative heat transfer at the surface. Convective cooling or heating in warmer months will contribute only a small percentage of the total because of the relatively small temperature difference between the air and the lake surface temperature. Back radiation typically occurs at night when the sky is clear, and can account for significant amount of cooling. The relatively warm water surface will radiate heat to the cooler sky. For example, on a clear night, a cooling rate of up to 50 Btu/h·ft² is possible from a lake 25°F warmer than the sky. The last mode of heat transfer, conduction to the ground, does not play a major role in lake cooling (Pezent and Kavanaugh 1990).

To put these heat transfer rates in perspective, consider a 1 acre (43,560 ft²) lake used in connection with a 10 ton (120,000 Btu/h) heat pump. In cooling mode, the unit rejects approximately 150,000 Btu/h to the lake. This is 3.4 Btu/h·ft², or approximately 1% of the maximum heat gain from solar radiation in the summer. In winter, a 10 ton heat pump absorbs only about 90,000 Btu/h, or 2.1 Btu/h·ft², from the lake.

Thermal Patterns in Lakes

The maximum density of water occurs at 39.2°F, not at the freezing point of 32°F. This phenomenon, in combination with the normal modes of heat transfer to and from lakes, produces temperature profiles advantageous to efficient heat pump operation. In the winter, the coldest water is at the surface. It tends to remain at the surface and freeze. The bottom of a deep lake stays 5 to 10°F warmer than the surface. This condition is referred to as winter stagnation. The warmer water is a better heat source than the colder water at the surface.

As spring approaches, surface water warms until the temperature approaches the maximum density point of 39.2°F. The winter stratification becomes unstable and circulation loops begin to develop from top to bottom. This condition of spring overturn (Peirce 1964) causes the lake temperature to become fairly uniform.

Later in the spring as water temperatures rise above 45°F, the circulation loops are in the upper portion of the lake. This pattern continues throughout the summer. The upper portion of the lake remains relatively warm, with evaporation cooling the lake and solar radiation warming it. The lower portion (hypolimnion) of the lake remains cold because most radiation is absorbed in the upper zone. Circulation loops do not penetrate to the lower zone, and conduction to the ground is quite small. The result is that, in deeper lakes with small or medium inflows, the upper zone is 70 to 90°F, the lower zone is 40 to 55°F, and the intermediate zone (thermocline) has a sharp change in temperature within a small change in depth. This condition is referred to as summer stagnation.

As fall begins, the water surface begins to cool by radiation and evaporation. With the approach of winter, the upper portion begins to cool towards the freezing point and the lower levels approach the maximum density temperature of 39.2°F. An ideal temperature-versus-depth chart is shown in Figure 29 for each of the four seasons (Peirce 1964).

Many lakes do exhibit near-ideal temperature profiles. However, (1) high inflow/outflow rates, (2) insufficient depth for stratification, (3) level fluctuation, (4) wind, and (5) lack of enough cold weather to establish sufficient amounts of cold water necessary for summer stratification can disrupt the profile. Therefore, a thermal survey of the lake should be conducted or existing surveys of similar lakes in similar geographic locations should be consulted.
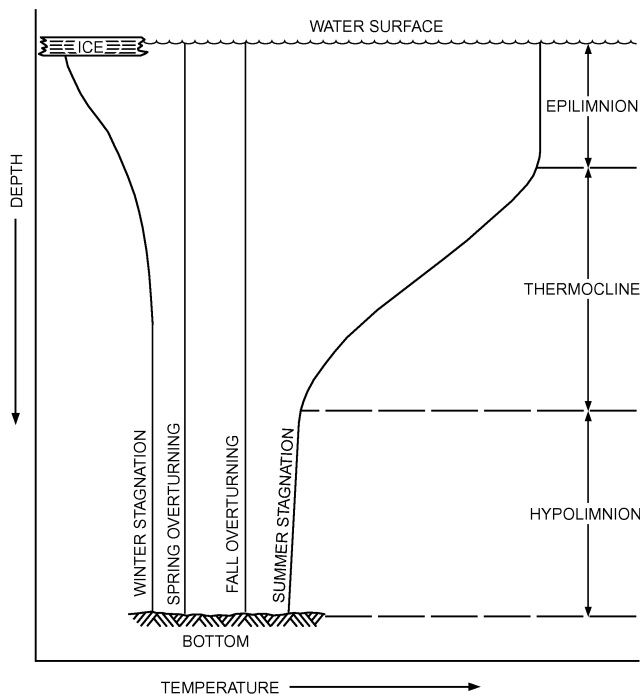
Fig. 29 Idealized Diagram of Annual Cycle of Thermal Stratification in Lakes

A. LOOSE BUNDLE COIL

B. TIGHT BUNDLE COIL WITH SPACERS
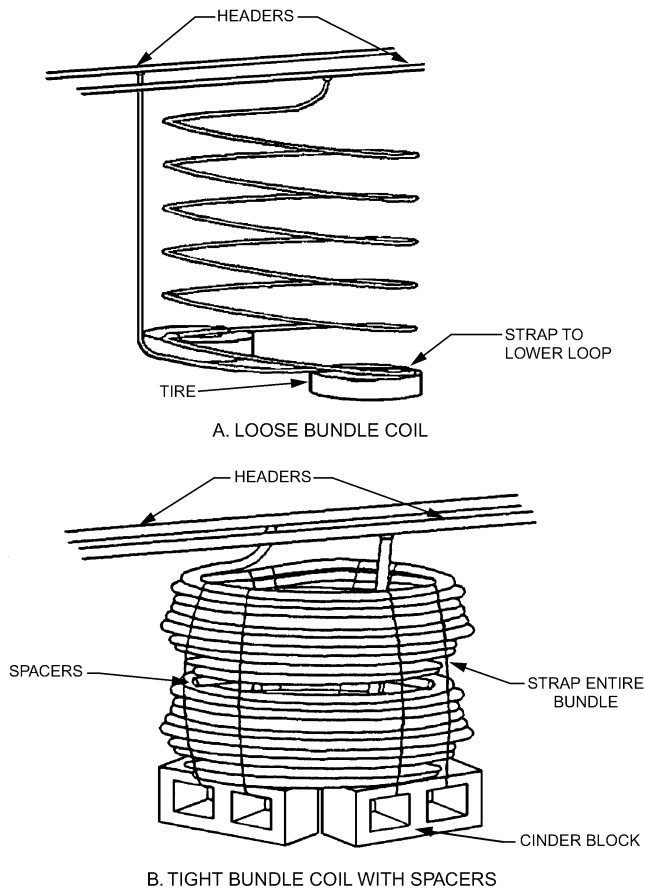
Fig. 30 Closed-Loop Lake Coil in Bundles
(Kavanaugh 1991)

Closed-Loop Lake Water Heat Pump

The closed-loop lake water heat pump shown in Figure 30 has several advantages over the open loop. One advantage is the reduced fouling resulting from the circulation of clean water (or water/antifreeze solution) through the heat pump. A second advantage is the reduced pumping-power requirement because of the absence of an elevation head from the lake surface to the heat pumps. A third advantage of a closed loop is that it is the only type recommended if a lake temperature below 40°F is possible. The outlet temperature of the fluid is about 6°F below that of the inlet at a flow of 3 gpm per ton. Frosting occurs on heat exchanger surfaces when the bulk water temperature is in the 34 to 38°F range.

A closed-loop system has several disadvantages. Heat pump performance drops slightly because the circulation fluid temperature drops 4 to 12°F below the lake temperature. A second disadvantage is the possibility of damage to coils in public lakes. Thermally fused polyethylene loops are much more resistant to damage than copper, glued plastic (PVC), or tubing with band-clamped joints. The third possible disadvantage is fouling on the outside of the lake coil, particularly in murky lakes or where coils are located on or near the lake bottom.

Polyethylene (PE 3408) is recommended for all intake piping. All connections must be either thermally socket-fused or butt-fused. These plastic pipes should also have protection from UV radiation, especially when near the surface. Polyvinyl chloride (PVC) pipe and plastic pipe with band-clamped joints are not recommended.

The piping networks of closed-loop systems resemble those used in ground-coupled heat pump systems. Both a large-diameter header between the heat pump and lake coil and several parallel loops of piping in the lake are required. Loops are spread out to limit thermal interference, hot spots, and cold pockets. Although this layout is preferred in terms of performance, installation is more time-consuming. Many contractors simply unbind plastic pipe coils and submerge them in a loose bundle. Some compensation for thermal interference is obtained by making bundled coils longer than the spread coils. A diagram of this type of installation is shown in Figure 30.

Copper coils have also been used successfully. Copper tubes have a very high thermal conductivity, so coils only one-fourth to one-third the length of plastic coils are required. However, copper pipe does not have the durability of PE 3408 or polybutylene, and if fouling is possible, coils must be significantly longer.

Antifreeze Requirements

Closed-loop horizontal and surface water heat exchanger systems often require antifreeze in the circulating water in locations with significant heating seasons. Antifreeze may not be needed in a comparable vertical borehole heat exchanger, because the deep ground temperature is essentially constant. At a depth of 6 ft, a typical value for horizontal heat exchangers, ground temperature varies by approximately ±10°F. Even if the mean ground temperature is 60°F in late winter, ground temperature at a 6 ft depth drops to 50°F. The heat extraction process lowers the temperature even further around the heat exchanger pipes, probably by an additional 10°F or more. Even with good heat transfer to the circulating water, the entering water temperature (leaving the ground heat exchanger) would be around 40°F. Lakes that freeze at the surface in the winter approach 39°F at the bottom, yielding nearly the same margin of safety against freezing of the circulating fluid. An additional 10°F temperature difference is usually needed in the heat pump's refrigerant-to-water heat exchanger to transfer heat to the refrigerant. Having a refrigerant-to-water coil surface temperature below the freezing point of water risks growing a layer of ice on the water side of the heat exchanger. In the best case, coil icing would restrict and may eventually block the flow of water and cause a shutdown.

In the worst case, the ice could burst the tubing in the coil and require a major service expense.

Several factors must be considered when selecting an antifreeze for a ground-loop heat exchanger; the most important are (1) effect on system life-cycle cost, (2) corrosivity, (3) leakage, (4) health risks, (5) fire risks, (6) environmental risks from spills or disposal, and (7) risk of future use (acceptability of the antifreeze over the life of the system). A study by Heinonen and Tapscott (1996) of six anti-freezes against these seven criteria is summarized in Table 16. No single material satisfies all criteria. Methanol and ethanol have good viscosity characteristics at low temperatures, yielding lower-than-average pumping power requirements. However, in concentrated forms they both pose a significant fire hazard. Methanol is also toxic, eliminating it from consideration in areas that require non-toxic antifreeze to be used. Propylene glycol had no major concerns, with only leakage and pumping-power requirements prompting minor concerns. Potassium acetate, calcium magnesium acetate (CMA), and urea have favorable environmental and safety performance, but are all subject to significant leakage problems, which has limited their use.

Table 16 Suitability of Selected GCHP Antifreeze Solutions

Category	Methanol	Ethanol	Propylene Glycol	Potassium Acetate	CMA	Urea
Life-cycle cost	***	***	**[1]	**[1]	**[1]	***
Corrosion	**[2]	**[3]	***	**	**[4]	*[5]
Leakage	***	**[6]	**[6]	*[7]	*[8]	*[9]
Health risk	*[10,11]	**[10,12]	***[10]	***[10]	***[10]	***[10]
Fire risk	*[13]	*[13]	***[14]	***	***	***
Environment risk	**[15]	**[15]	***	**[15]	**[15]	***
Future-use risk	*[16]	**[17]	***	**[18]	**[19]	**[19]

Key:
*   Potential problems, caution in use required
**   Minor potential for problems
***   Little or no potential for problems

Category	Notes
Life-cycle cost	1. Higher-than-average installation and energy costs.
Corrosion	2. High black iron and cast iron corrosion rates.
	3. High black iron and cast iron, copper and copper alloy corrosion rates.
	4. Medium black iron, copper and copper alloy corrosion rates.
	5. Medium black iron, high cast iron, and extremely high copper and copper alloy corrosion rates.
Leakage	6. Minor leakage observed.
	7. Moderate leakage observed. Extensive leakage reported in installed systems.
	8. Moderate leakage observed.
	9. Massive leakage observed.
Health risk	10. Protective measures required with use. See Material Safety Data Sheet (MSDS).
	11. Prolonged exposure can cause headaches, nausea, vomiting, dizziness, blindness, liver damage, and death. Use of proper equipment and procedures reduces risk significantly.
	12. Confirmed human carcinogen.
Fire Risk	13. Pure fluid only. Little risk when diluted with water in antifreeze.
	14. Very minor potential for pure fluid fire at elevated temperatures.
Environment risk	15. Water pollution.
Future-use risk	16. Toxicity and fire concerns. Prohibited in some locations.
	17. Toxicity, fire, and environmental concerns.
	18. Potential leakage concerns.
	19. Not currently used as GSHP antifreeze solution. May be difficult to obtain approval for use.

Source: Heinonen and Tapscott (1996).

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CHAPTER 33

SOLAR ENERGY USE

THE sun radiates considerable energy onto the earth. Putting that diffuse, rarely over 300 Btu/h·ft^2 energy to work has led to the creation of many types of devices to convert that energy into useful forms, mainly heat and electricity. How that energy is valued economically drives the ebb and flow of the global solar industry. This chapter discusses several different types of solar equipment and system designs for various HVAC applications, as well as methods to determine the solar resource.

Worldwide, solar energy use varies in application and degree. In China and, to a lesser extent, Australasia, solar energy is widely used, particularly for water heating. In Europe, government incentives have fostered use of photovoltaic and thermal systems for both domestic hot-water and space heating. In the Middle East, solar power is used for desalination and absorption air conditioning. Solar energy use in the United States is relatively modest, driven by tax policy and utility programs that generally react to energy shortages or the price of oil.

Recent interest in sustainability and green buildings has led to an increased focus on solar energy devices for their nonpolluting and renewable qualities; replacing fossil fuel with domestic, renewable energy sources can also enhance national security by reducing dependence on imported energy.

For more information on the use of solar and other energy sources, see the Energy Information Administration (EAI) of the U.S. Department of Energy (www.eai.doe.gov) and the International Energy Agency (www.iea.org).

QUALITY AND QUANTITY OF SOLAR ENERGY

Solar Constant

Solar energy approaches the earth as electromagnetic radiation, with wavelengths ranging from 0.1 μm (x-rays) to 100 m (radio waves). The earth maintains a thermal equilibrium between the annual input of shortwave radiation (0.3 to 2.0 μm) from the sun and the outward flux of longwave radiation (3.0 to 30 μm). Only a limited band need be considered in terrestrial applications, because 99% of the sun's radiant energy has wavelengths between 0.28 and 4.96 μm. The current value of the solar constant (which is defined as the intensity of solar radiation on a surface normal to the sun's rays, just beyond the earth's atmosphere at the average earth-sun distance) is 433 Btu/h·ft^2. The section on Determining Incident Solar Flux in Chapter 31 of the 2005 *ASHRAE Handbook—Fundamentals* has further information on this topic.

Solar Angles

The axis about which the earth rotates is tilted at an angle of 23.45° to the plane of the earth's orbital plane and the sun's equator.

The preparation of this chapter is assigned to TC 6.7, Solar Energy Utilization.

The earth's tilted axis results in a day-by-day variation of the angle between the earth-sun line and the earth's equatorial plane, called the **solar declination** δ. This angle varies with the date, as shown in Table 1 for the year 1964 and in Table 2 for 1977. For other dates, the declination may be estimated by the following equation:

$$\delta = 23.45 \sin\left[360° \times \frac{284 + N}{365}\right] \quad (1)$$

where N = year day, with January 1 = 1. For values of N, see Tables 1 and 2.

The relationship between δ and the date from year to year varies to an insignificant degree. The daily change in the declination is the primary reason for the changing seasons, with their variation in the distribution of solar radiation over the earth's surface and the varying number of hours of daylight and darkness. Note that the following sections are based in the northern hemisphere; sites in the southern hemisphere will be 180° from the examples (e.g., a solar panel should face north).

The earth's rotation causes the sun's apparent motion (Figure 1). The position of the sun can be defined in terms of its altitude β above the horizon (angle HOQ) and its azimuth φ, measured as angle HOS in the horizontal plane.

At solar noon, the sun is exactly on the meridian, which contains the south-north line. Consequently, the solar azimuth φ is 0°. The noon altitude β_N is given by the following equation as

$$\beta_N = 90° - LAT + \delta \quad (2)$$

where LAT = latitude.

Because the earth's daily rotation and its annual orbit around the sun are regular and predictable, the solar altitude and azimuth may be readily calculated for any desired time of day when the latitude, longitude, and date (declination) are specified. Apparent solar time (AST) must be used, expressed in terms of the hour angle H, where

$$H = (\text{Number of hours from solar noon}) \times 15°$$
$$= \frac{\text{Number of minutes from solar noon}}{4} \quad (3)$$

Solar Time

Apparent solar time (AST) generally differs from local standard time (LST) or daylight saving time (DST), and the difference can be significant, particularly when DST is in effect. Because the sun appears to move at the rate of 360° in 24 h, its apparent rate of motion is 4 min per degree of longitude. The AST can be determined from the following equation:

Table 1   Date, Declination, and Equation of Time for the 21st Day of Each Month of 1964, with Data (*A, B, C*)
Used to Calculate Direct Normal Radiation Intensity at the Earth's Surface

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Year Day	21	52	80	111	141	172	202	233	264	294	325	355
Declination δ, degrees	−19.9	−10.6	0.0	+11.9	+20.3	+23.45	+20.5	+12.1	0.0	−10.7	−19.9	−23.45
Equation of time, minutes	−11.2	−13.9	−7.5	+1.1	+3.3	−1.4	−6.2	−2.4	+7.5	+15.4	+13.8	+1.6
Solar noon		late			early			late			early	
A, Btu/h·ft^2	390	385	376	360	350	345	344	351	365	378	387	391
B, dimensionless	0.142	0.144	0.156	0.180	0.196	0.205	0.207	0.201	0.177	0.160	0.149	0.142
C, dimensionless	0.058	0.060	0.071	0.097	0.121	0.134	0.136	0.122	0.092	0.073	0.063	0.057

A = apparent solar irradiation at air mass zero for each month.   *C* = ratio of diffuse radiation on horizontal surface to direct normal irradiation.
B = atmospheric extinction coefficient.

Table 2   Solar Position Data for 1977

Date		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
1	Year Day	1	32	60	91	121	152	182	213	244	274	305	335
	Declination δ	−23.0	−17.0	−7.4	+4.7	+15.2	+22.1	+23.1	+17.9	+8.2	−3.3	−14.6	−21.9
	Eq of Time	−3.6	−13.7	−12.5	−4.0	+2.9	+2.4	−3.6	−6.2	+0.0	+10.2	+16.3	+11.0
6	Year Day	6	37	65	96	126	157	187	218	249	279	310	340
	Declination δ	−22.4	−15.5	−5.5	+6.6	+16.6	+22.7	+22.7	+16.6	+6.7	−5.3	−16.1	−22.5
	Eq of Time	−5.9	−14.2	−11.4	−2.5	+3.5	+1.6	−4.5	−5.8	+1.6	+11.8	+16.3	+9.0
11	Year Day	11	42	70	101	131	162	192	223	254	284	315	345
	Declination δ	−21.7	−13.9	−3.5	−8.5	+17.9	+23.1	+22.1	+15.2	+4.4	−7.2	−17.5	−23.0
	Eq of Time	−8.0	−14.4	−10.2	−1.1	+3.7	+0.6	−5.3	−5.1	+3.3	+13.1	+15.9	+6.8
16	Year Day	16	47	75	106	136	167	197	228	259	289	320	350
	Declination δ	−20.8	−12.2	−1.6	+10.3	+19.2	+23.3	+21.3	+13.6	+2.5	−8.7	−18.8	−23.3
	Eq of Time	−9.8	−14.2	−8.8	+0.1	+3.8	−0.4	−5.9	−4.3	+5.0	+14.3	+15.2	+4.4
21	Year Day	21	52	80	111	141	172	202	233	264	294	325	355
	Declination δ	−19.6	−10.4	+0.4	+12.0	+20.3	+23.4	+20.6	+12.0	+0.5	−10.8	−20.0	−23.4
	Eq of Time	−11.4	−13.8	−7.4	+1.2	+3.6	−1.5	−6.2	−3.1	+6.8	+15.3	+14.1	+2.0
26	Year Day	26	57	85	116	146	177	207	238	269	299	330	360
	Declination δ	−18.6	−8.6	+2.4	+13.6	+21.2	+23.3	+19.3	+10.3	−1.4	−12.6	−21.0	−23.4
	Eq of Time	−12.6	−13.1	−5.8	+2.2	+3.2	−2.6	−6.4	−1.8	+8.6	+15.9	+12.7	−0.5

Source: ASHRAE *Standard* 93-2003.
Notes: Units for declination are angular degrees; units for equation of time are minutes. Values of declination and equation of time vary slightly for specific dates in other years.

$$AST = LST + \text{Equation of time} + (4 \text{ min})(LST \text{ meridian} - \text{Local longitude}) \quad (4)$$

The longitudes of the seven standard time meridians that affect North America are Atlantic ST, 60°; Eastern ST, 75°; Central ST, 90°; Mountain ST, 105°; Pacific ST, 120°; Yukon ST, 135°; and Alaska-Hawaii ST, 150°.

The equation of time is the measure, in minutes, of the extent by which solar time, as determined by a sundial, runs faster or slower than local standard time (LST), as determined by a clock that runs at a uniform rate. Table 1 gives values of the declination of the sun and the equation of time for the 21st day of each month for the year 1964 (when the ASHRAE solar radiation tables were first calculated), and Table 2 gives values of δ and the equation of time for six days each month for the year 1977.

Example 1. Find AST at noon DST on July 21 for Washington, D.C., longitude = 77°, and for Chicago, longitude = 87.6°.

Solution: Noon DST is actually 11:00 AM LST. Washington is in the eastern time zone, and the LST meridian is 75°. From Table 1, the equation of time for July 21 is –6.2 min. Thus, from Equation (4), noon DST for Washington is actually

$$AST = 11:00 - 6.2 + 4(75 - 77) = 10:45.8 \text{ AST} = 10.76 \text{ h}$$

Chicago is in the central time zone, and the LST meridian is 90°. Thus, from Equation (4), noon central DST is

$$AST = 11:00 - 6.2 + 4(90 - 87.6) = 11:03.4 \text{ AST} = 11.06 \text{ h}$$

The hour angles *H* for these two examples (see Figure 2) are
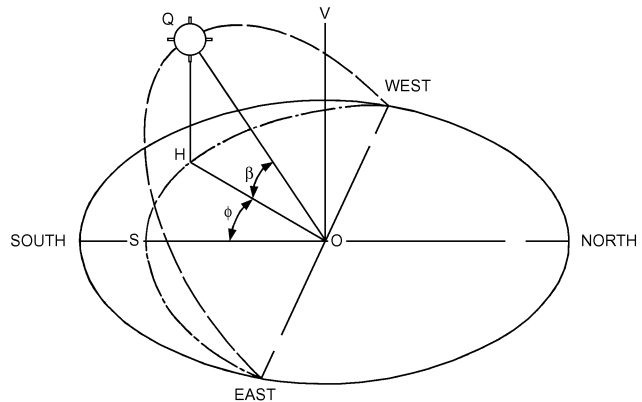
Fig. 1   Apparent Daily Path of the Sun Showing Solar Altitude (β) and Solar Azimuth (φ)

for Washington, $H = (12.00 - 10.76)15° = 18.6°$ east
for Chicago, $H = (12.00 - 11.06)15° = 14.10°$ east

To find the solar altitude β and the azimuth φ when the hour angle *H*, latitude LAT, and declination δ are known, the following equations may be used:

$$\sin \beta = \cos(LAT) \cos \delta \cos H + \sin(LAT) \sin \delta \quad (5)$$

$$\sin \phi = \cos \delta \sin H / \cos \beta \quad (6)$$

or $$\cos \phi = \frac{\sin \beta \sin(LAT) - \sin \delta}{\cos \beta \cos(LAT)} \quad (7)$$
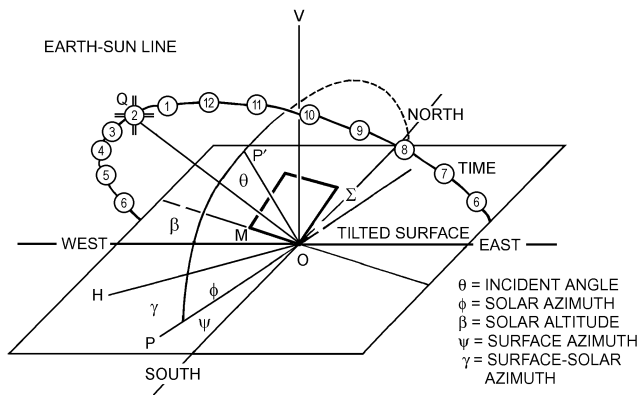
Fig. 2   Solar Angles with Respect to a Tilted Surface

Tables 15 through 21 in Chapter 29 of the 1997 *ASHRAE Handbook—Fundamentals* give values for latitudes from 16 to 64° north. For any other date or latitude, interpolation between the tabulated values will give sufficiently accurate results. The section on Determining Solar Angle in Chapter 31 of the 2005 *ASHRAE Handbook—Fundamentals* provides tables and equations for these calculations as well.

Incident Angle

The angle between the line normal to the irradiated surface (OP′ in Figure 2) and the earth-sun line OQ is called the incident angle θ. It is important in solar technology because it affects the intensity of the direct component of solar radiation striking the surface and the surface's ability to absorb, transmit, or reflect the sun's rays.

To determine θ, the surface azimuth ψ and the surface-solar azimuth γ must be known. The surface azimuth (angle POS in Figure 2) is the angle between the south-north line SO and the normal PO to the intersection of the irradiated surface with the horizontal plane, shown as line OM. The surface-solar azimuth, angle HOP, is designated by γ and is the angular difference between the solar azimuth φ and the surface azimuth ψ. For surfaces facing east of south, γ = φ − ψ in the morning and γ = φ + ψ in the afternoon. For surfaces facing west of south, γ = φ + ψ in the morning and γ = φ − ψ in the afternoon. For south-facing surfaces, ψ = 0°, so ψ = φ for all conditions. The angles δ, β, and φ are always positive.

For a surface with a tilt angle Σ (measured from the horizontal), the angle of incidence θ between the direct solar beam and the normal to the surface (angle QOP′ in Figure 2) is given by

$$\cos \theta = \cos \beta \cos \gamma \sin \Sigma + \sin \beta \cos \Sigma \qquad (8)$$

For vertical surfaces, Σ = 90°, cos Σ = 0, and sin Σ = 1.0, so Equation (8) becomes

$$\cos \theta = \cos \beta \cos \gamma \qquad (9)$$

For horizontal surfaces, Σ = 0°, sin Σ = 0, and cos Σ = 1.0, so Equation (8) leads to

$$\theta_H = 90° - \beta \qquad (10)$$

Example 2. Find θ for a south-facing surface tilted upward 30° from the horizontal at 40° north latitude at 4:00 PM, AST, on August 21.

Solution: From Equation (3), at 4:00 PM on August 21,

$$H = 4 \times 15° = 60°$$

From Table 1,

$$\delta = 12.1°$$

From Equation (5),

$$\sin \beta = \cos 40° \cos 12.1° \cos 60° + \sin 40° \sin 12.1°$$
$$\beta = 30.6°$$

From Equation (6),

$$\sin \phi = \cos 12.1° \sin 60° / \cos 30.6°$$
$$\phi = 79.7°$$

The surface faces south, so φ = γ. From Equation (8),

$$\cos \theta = \cos 30.6° \cos 79.7° \sin 30° + \sin 30.6° \cos 30°$$
$$\theta = 58.8°$$

ASHRAE *Standard* 93 provides tabulated values of θ for horizontal and vertical surfaces and for south-facing surfaces tilted upward at angles equal to the latitude minus 10°, the latitude, the latitude plus 10°, and the latitude plus 20°. These tables cover the latitudes from 24° to 64° north, in 8° intervals.

Solar Spectrum

Beyond the earth's atmosphere, the effective blackbody temperature of the sun is 10,370°R. The maximum spectral intensity occurs at 0.48 μm in the green portion of the visible spectrum. Thekaekara (1973) presents tables and charts of the sun's extraterrestrial spectral irradiance from 0.120 to 100 μm, the range in which most of the sun's radiant energy is contained. The ultraviolet portion of the spectrum below 0.40 μm contains 8.73% of the total, another 38.15% is contained in the visible region between 0.40 and 0.70 μm, and the infrared region contains the remaining 53.12%.

Solar Radiation at the Earth's Surface

In passing through the earth's atmosphere, some of the sun's direct radiation I_D is scattered by nitrogen, oxygen, and other molecules, which are small compared to the wavelengths of the radiation; and by aerosols, water droplets, dust, and other particles with diameters comparable to the wavelengths (Gates 1966). This scattered radiation causes the sky to appear blue on clear days, and some of it reaches the earth as diffuse radiation I.

Attenuation of the solar rays is also caused by absorption, first by the ozone in the outer atmosphere, which causes a sharp cutoff at 0.29 μm of the ultraviolet radiation reaching the earth's surface (Figure 3). In the longer wavelengths, there are series of absorption bands caused by water vapor, carbon dioxide, and ozone. The total amount of attenuation at any given location is determined by (1) the length of the atmospheric path through which the rays travel and (2) the composition of the atmosphere. The path length is expressed in terms of the air mass *m*, which is the ratio of the mass of atmosphere in the actual earth-sun path to the mass that would exist if the sun were directly overhead at sea level (*m* = 1.0). For all practical purposes, at sea level, *m* = 1.0/sin β. Beyond the earth's atmosphere, *m* = 0.

Before 1967, solar radiation data were based on an assumed solar constant of 419.7 Btu/h·ft² and on a standard sea-level atmosphere containing the equivalent depth of 2.8 mm of ozone, 20 mm of precipitable moisture, and 300 dust particles per cm³. Threlkeld and Jordan (1958) considered the wide variation of water vapor in the atmosphere above the United States at any given time, and particularly the seasonal variation, which finds three times as much moisture in the atmosphere in midsummer as in December, January, and February. The basic atmosphere was assumed to be at sea level barometric pressure, with 2.5 mm of ozone, 200 dust particles per cm³, and an actual precipitable moisture content that varied throughout the year from 8 mm in midwinter to 28 mm in mid-July. Figure 4 shows the variation of the direct normal irradiation with solar altitude, as estimated for clear atmospheres and for an atmosphere with variable moisture content.

LIVE GRAPH
Click here to view
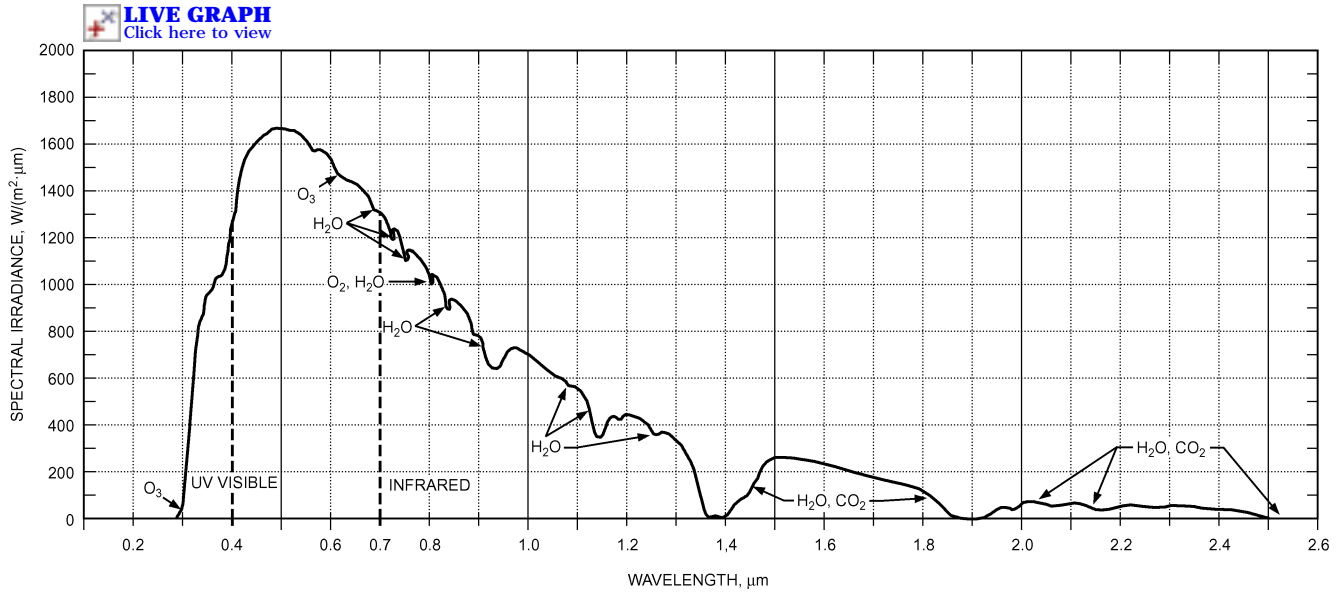
Fig. 3   Spectral Solar Irradiation at Sea Level for Air Mass = 1.0

LIVE GRAPH
Click here to view
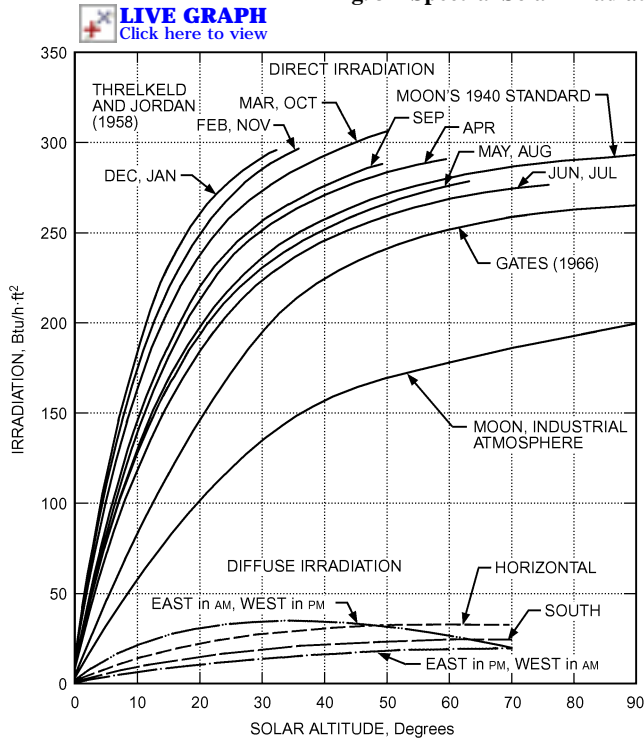
Fig. 4   Variation with Solar Altitude and Time of Year for Direct Normal Irradiation

Fig. 5   Clearness Numbers for the United States

Stephenson (1967) showed that the intensity of the direct normal irradiation I_{DN} at the earth's surface on a clear day can be estimated by the following equation:

$$I_{DN} = A e^{-B/\sin\beta} \tag{11}$$

where A, the apparent extraterrestrial irradiation at $m = 0$, and B, the atmospheric extinction coefficient, are functions of the date and take into account the seasonal variation of the earth-sun distance and the air's water vapor content.

The values of the parameters A and B given in Table 1 were selected so that the resulting value of I_{DN} would be closely agree with

the Threlkeld and Jordan (1958) values on average cloudless days. The values of I_{DN} given in Tables 15 through 21 in Chapter 29 of the 1997 *ASHRAE Handbook—Fundamentals* were obtained by using Equation (11) and data from Table 1. The values of solar altitude β and solar azimuth ϕ may be obtained from Equations (5) and (6). Additional information may be found in the Determining Incident Solar Flux section of Chapter 31 of the 2005 *ASHRAE Handbook—Fundamentals*.

Because local values of atmospheric water content and elevation can vary markedly from the sea-level average, the concept of **clearness number** was introduced to express the ratio between the actual clear-day direct irradiation intensity at a specific location and the intensity calculated for the standard atmosphere for the same location and date.

Figure 5 shows the Threlkeld-Jordan map of winter and summer clearness numbers for the continental United States. Irradiation values should be adjusted by the clearness numbers applicable to each particular location.

Design Values of Total Solar Irradiation

The total solar irradiation $I_{t\theta}$ of a terrestrial surface of any orientation and tilt with an incident angle θ is the sum of the direct component $I_{DN} \cos \theta$ plus the diffuse component $I_{d\theta}$ coming from the sky plus whatever amount of reflected shortwave radiation I_r may reach the surface from the earth or from adjacent surfaces:

$$I_{t\theta} = I_{DN}\cos\theta + I_{d\theta} + I_r \qquad (12)$$

The diffuse component is difficult to estimate because of its non-directional nature and its wide variations. Figure 4 shows typical values of diffuse irradiation of horizontal and vertical surfaces. For clear days, Threlkeld (1963) derived a dimensionless parameter (designated as C in Table 1), which depends on the dust and moisture content of the atmosphere and thus varies throughout the year:

$$C = \frac{I_{dH}}{I_{DN}} \qquad (13)$$

where I_{dH} is the diffuse radiation falling on a horizontal surface under a cloudless sky.

The following equation may be used to estimate the amount of diffuse radiation $I_{d\theta}$ that reaches a tilted or vertical surface:

$$I_{d\theta} = CI_{DN}F_{ss} \qquad (14)$$

where

$$F_{ss} = \frac{1+\cos\Sigma}{2} \qquad (15)$$
$$= \text{angle factor between the surface and the sky}$$

The reflected radiation I_r from the foreground is given by

$$I_r = I_{tH}\rho_g F_{sg} \qquad (16)$$

where

ρ_g = reflectance of the foreground
I_{tH} = total horizontal irradiation

$$F_{sg} = \frac{1+\cos\Sigma}{2} \qquad (17)$$
$$= \text{angle factor between surface and earth}$$

The intensity of the reflected radiation that reaches any surface depends on the nature of the reflecting surface and on the incident angle between the sun's direct beam and the reflecting surface. Many measurements made of the reflection (albedo) of the earth under varying conditions show that clean, fresh snow has the highest reflectance (0.87) of any natural surface.

Threlkeld (1963) gives values of reflectance for commonly encountered surfaces at solar incident angles from 0 to 70°. Bituminous paving generally reflects less than 10% of the total incident solar irradiation; bituminous and gravel roofs reflect from 12 to 15%; concrete, depending on its age, reflects from 21 to 33%. Bright green grass reflects 20% at $\theta = 30°$ and 30% at $\theta = 65°$.

The maximum daily amount of solar irradiation that can be received at any given location is that which falls on a flat plate with its surface kept normal to the sun's rays so it receives both direct and diffuse radiation. For fixed flat-plate collectors, the total amount of clear-day irradiation depends on the orientation and slope. As shown by Figure 6 for 40° north latitude, the total irradiation of horizontal surfaces reaches its maximum in midsummer, whereas vertical south-facing surfaces experience their maximum irradiation during the winter. These curves show the combined effects of the varying length of days and changing solar altitudes.

In general, flat-plate collectors are mounted at a fixed tilt angle Σ (above the horizontal) to give the optimum amount of irradiation for each purpose. Collectors intended for winter heating benefit from higher tilt angles than those used to operate cooling systems in summer. Solar water heaters, which should operate satisfactorily throughout the year, require an angle that is a compromise between the optimal values for summer and winter. Figure 6 shows the monthly variation of total day-long irradiation on the 21st day of each month at 40° north latitude for flat surfaces with various tilt angles.
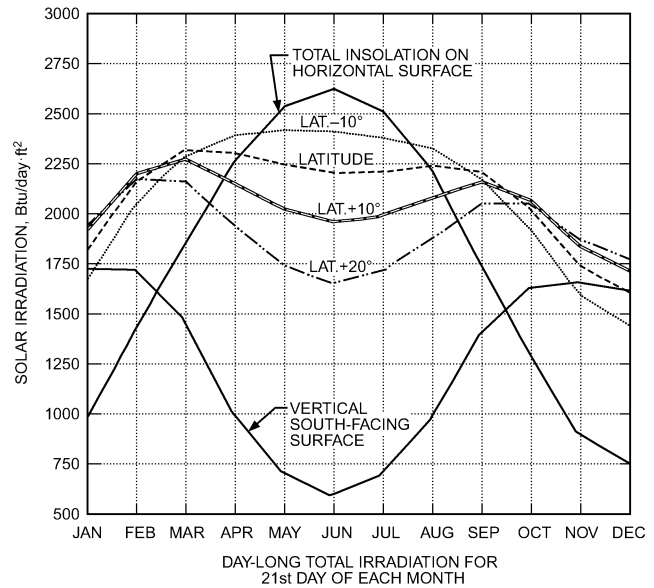
Fig. 6   Total Daily Irradiation for Horizontal, Tilted, and Vertical Surfaces at 40° North Latitude

Tables in ASHRAE *Standard* 93 give the total solar irradiation for the 21st day of each month at latitudes 24 to 64° north on surfaces with the following orientations: normal to the sun's rays (direct normal data do not include diffuse irradiation); horizontal; south-facing, tilted at (LAT–10), LAT, (LAT+10), (LAT+20), and 90° from the horizontal. The day-long total irradiation for fixed surfaces is highest for those that face south, but a deviation in azimuth of 15 to 20° causes only a small reduction.

Solar Energy for Flat-Plate Collectors

The preceding data apply to clear days. The irradiation for average days may be estimated for any specific location by referring to publications of the U.S. Weather Service. The *Climatic Atlas of the United States* (U.S. GPO 2005) gives maps of monthly and annual values of percentage of possible sunshine, total hours of sunshine, mean solar radiation, mean sky cover, wind speed, and wind direction. Chapter 28 in the 2005 *ASHRAE Handbook—Fundamentals* also provides several sources for obtaining solar data.

The total daily horizontal irradiation data reported by the U.S. Weather Bureau for approximately 100 stations before 1964 show that the percentage of total clear-day irradiation is approximately a linear function of the percentage of possible sunshine. The irradiation is not zero for days when the percentage of possible sunshine is reported as zero, because substantial amounts of energy reach the earth in the form of diffuse radiation. Instead, the following relationship exists for the percentage of possible sunshine:

$$\frac{\text{Day-long actual } I_{tH}}{\text{Clear day } I_{tH}}100 = a + b \qquad (18)$$

where a and b are constants for any specified month at any given location. See also Duffie and Beckman (1992) and Jordan and Liu (1977).

Longwave Atmospheric Radiation

In addition to the shortwave (0.3 to 2.0 μm) radiation it receives from the sun, the earth receives longwave radiation (4 to 100 μm, with maximum intensity near 10 μm) from the atmosphere. In turn, a surface on the earth emits longwave radiation q_{Rs} in accordance with the Stefan-Boltzmann law:

Table 3   Sky Emittance and Amount of Precipitable Moisture Versus Dew-Point Temperature

Dew Point, °F	Sky Emittance, e_{at}	Precipitable Water, in.
−20	0.68	0.12
−10	0.71	0.16
0	0.73	0.18
10	0.76	0.22
20	0.77	0.29
30	0.79	0.41
40	0.82	0.57
50	0.84	0.81
60	0.86	1.14
70	0.88	1.61

$$q_{Rs} = e_s \sigma T_s^4 \tag{19}$$

where

e_s = surface emittance
σ = Stefan-Boltzmann constant, 0.1712×10^{-8} Btu/h·ft²·°R⁴
T_s = absolute temperature of surface, °R

For most nonmetallic surfaces, the longwave hemispheric emittance is high, ranging from 0.84 for glass and dry sand to 0.95 for black built-up roofing. For highly polished metals and certain selective surfaces, e_s may be as low as 0.05 to 0.20.

Atmospheric radiation comes primarily from water vapor, carbon dioxide, and ozone (Bliss 1961); very little comes from oxygen and nitrogen, although they make up 99% of the air.

Approximately 90% of the incoming atmospheric radiation comes from the lowest 300 ft. Thus, air conditions at ground level largely determine the magnitude of the incoming radiation. Downward radiation from the atmosphere q_{Rat} may be expressed as

$$q_{Rat} = e_{at} \sigma T_{at}^4 \tag{20}$$

The emittance of the atmosphere is a complex function of air temperature and moisture content. The dew point of the atmosphere near the ground determines the total amount of moisture in the atmosphere above the place where the dry-bulb and dew-point temperatures of the atmosphere are determined (Reitan 1963). Bliss (1961) found that the emittance of the atmosphere is related to the dew-point temperature, as shown by Table 3.

The apparent sky temperature is defined as the temperature at which the sky (as a blackbody) emits radiation at the rate actually emitted by the atmosphere at ground level temperature with its actual emittance e_{at}. Then,

$$\sigma T_{sky}^4 = e_{at} \sigma T_{at}^4 \tag{21}$$

or

$$T_{sky}^4 = e_{at} T_{at}^4 \tag{22}$$

Example 3. Consider a summer night condition when ground-level temperatures are 65°F dew point and 85°F dry bulb. From Table 3, e_{at} at 65°F dew point is 0.87, and the apparent sky temperature is

$$T_{sky} = 0.87^{0.25}(85 + 459.6) = 526.0°R$$

Thus, T_{sky} = 526.0 − 459.6 = 66.4°F, which is 18.6°F below the ground-level dry-bulb temperature.

For a winter night in Arizona, when temperatures at ground level are 60°F db and 25°F dp, from Table 3, the emittance of the atmosphere is 0.78, and the apparent sky temperature is 488.3°R or 28.7°F.

A simple relationship, which ignores vapor pressure of the atmosphere, may also be used to estimate the apparent sky temperature:

$$T_{sky} = 0.0411 T_{at}^{1.5} \tag{23}$$

where *T* is in degrees Rankine.
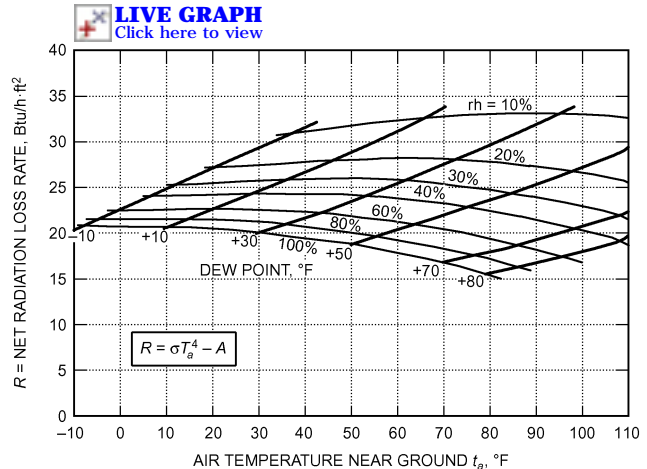
Fig. 7   Radiation Heat Loss to Sky from Horizontal Blackbody

If the temperature of the radiating surface is assumed to equal the atmospheric temperature, the heat loss from a black surface (e_s = 1.0) may be found from Figure 7.

Example 4. For the conditions in the previous example for summer, 85°F db and 65°F dp, the rate of radiative heat loss is about 23 Btu/h·ft². For winter, 60°F db and 25°F dp, the heat loss is about 27 Btu/h·ft².

Where a rough, unpainted roof is used as a heat dissipater, the rate of heat loss rises rapidly as the surface temperature goes up. For the summer example, a painted metallic roof, e_s = 0.96, at 100°F (559.6°R) will have a heat loss rate of

$$q_{RAD} = 0.96 \times 0.1713 \times 10^{-8}[559.6^4 - 526.0^4]$$
$$= 35.4 \text{ Btu/h·ft}^2$$

This analysis shows that radiation alone is not an effective means of dissipating heat under summer conditions of high dew-point and ambient temperatures. In spring and fall, when both the dew-point and dry-bulb temperatures are relatively low, radiation becomes much more effective.

On overcast nights, when cloud cover is low, the clouds act much like blackbodies at ground-level temperature, and virtually no heat can be lost by radiation. Exchange of longwave radiation between the sky and terrestrial surfaces occurs in the daytime as well as at night, but the much greater magnitude of the solar irradiation masks the longwave effects.

SOLAR ENERGY COLLECTION

Solar energy can be converted to (1) chemical, (2) electrical, and (3) thermal processes. Photosynthesis is a chemical process that produces food and converts CO_2 to O_2. Photovoltaic cells convert solar energy to electricity. The section on Photovoltaic Applications discusses some applications for these devices. The thermal conversion process, the primary subject of this chapter, provides thermal energy for space heating and cooling, domestic water heating, power generation, distillation, and process heating.

Solar Heat Collection by Flat-Plate Collectors

The solar irradiation calculation methods presented in the previous sections may be used to estimate how much energy is likely to be available at any specific location, date, and time of day for collection by either a concentrating device, which uses only the direct rays of the sun, or by a flat-plate collector, which can use both direct and diffuse irradiation. Temperatures needed for space heating and cooling do not exceed 200°F, even for absorption refrigeration, and they can be attained with carefully designed flat-plate collectors. Depending on the load and ambient temperatures, single-effect absorption systems can use energizing temperatures of 110 to 230°F.

A flat-plate collector generally consists of the following components (see Figure 8):

- **Glazing.** One or more sheets of glass or other radiation-transmitting material.
- **Tubes, fins, or passages.** To conduct or direct the heat transfer fluid from the inlet to the outlet.
- **Absorber plates.** Flat, corrugated, or grooved plates, to which the tubes, fins, or passages are attached. The plate may be integral with the tubes.
- **Headers or manifolds.** To admit and discharge the heat transfer fluid.

- **Insulation.** To minimize heat loss from the back and sides of the collector.
- **Container or casing.** To surround the other components and protect them from dust, moisture, etc.

Flat-plate collectors have been built in a wide variety of designs from many different materials (Figure 9). They have been used to heat fluids such as water, water plus an antifreeze additive, or air. Their major purpose is to collect as much solar energy as possible at the lowest possible total cost. The collector should also have a long effective life, despite the adverse effects of the sun's ultraviolet radiation; corrosion or clogging because of acidity, alkalinity, or hardness of the heat transfer fluid; freezing or air-binding in the case of water, or deposition of dust or moisture in the case of air; and breakage of the glazing because of thermal expansion, hail, vandalism, or other causes. These problems can be minimized by using tempered glass.

Glazing Materials

Glass has been widely used to glaze flat-plate solar collectors because it can transmit as much as 90% of the incoming shortwave solar irradiation while transmitting very little of the longwave radiation emitted outward from the absorber plate. Glass with low iron content has a relatively high transmittance for solar radiation (approximately 0.85 to 0.90 at normal incidence), but its transmittance is essentially zero for the longwave thermal radiation (5.0 to 50 µm) emitted by sun-heated surfaces.

Plastic films and sheets also have high shortwave transmittance, but because most usable varieties also have transmission bands in the middle of the thermal radiation spectrum, their longwave transmittances may be as high as 0.40.

Plastics are also generally limited in the temperatures they can sustain without deteriorating or undergoing dimensional changes. Only a few kinds of plastics can withstand the sun's ultraviolet radiation for long periods. However, they are not broken by hail and other stones and, in the form of thin films, they are completely flexible and have low mass.

The glass generally used in solar collectors may be either single-strength (0.085 to 0.100 in. thick) or double-strength (0.115 to 0.133 in. thick). The commercially available grades of window and greenhouse glass have normal incidence transmittances of about
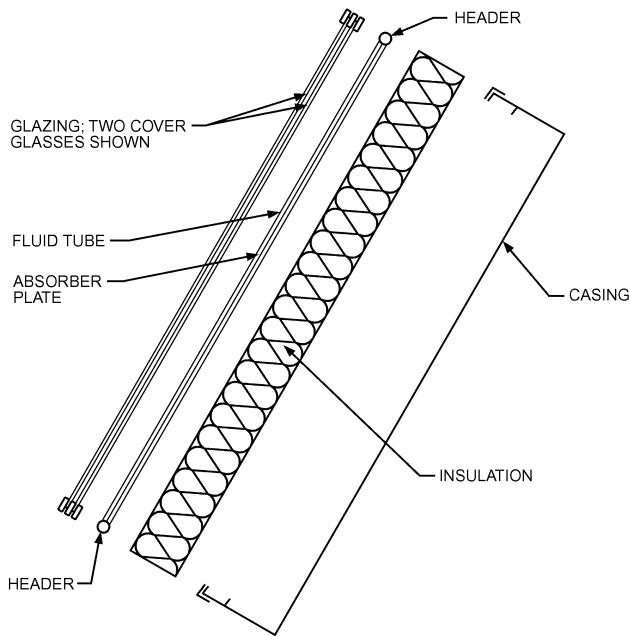
Fig. 8   Exploded Cross Section Through Double-Glazed Solar Water Heater
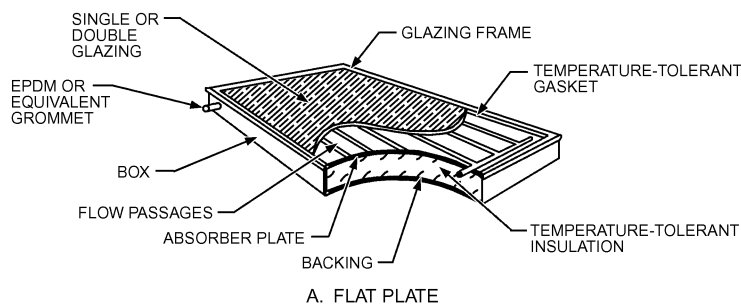
A. FLAT PLATE
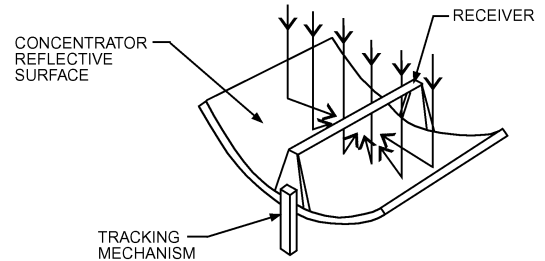
B. PARABOLIC TROUGH
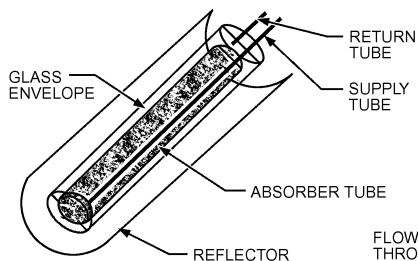
C. EVACUATED TUBES
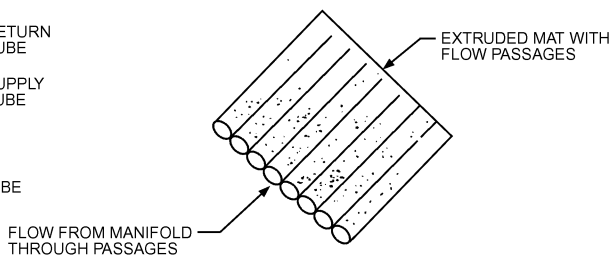
D. UNGLAZED EPDM COLLECTOR
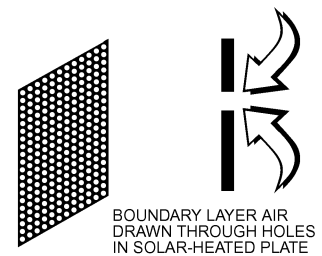
E. PERFORATED PLATE

Fig. 9   Various Types of Solar Collectors

Table 4 Variation with Incident Angle of Transmittance for Single and Double Glazing and Absorptance for Flat Black Paint

Incident Angle, Deg	Transmittance		Absorptance for Flat Black Paint
	Single Glazing	Double Glazing	
0	0.87	0.77	0.96
10	0.87	0.77	0.96
20	0.87	0.77	0.96
30	0.87	0.76	0.95
40	0.86	0.75	0.94
50	0.84	0.73	0.92
60	0.79	0.67	0.88
70	0.68	0.53	0.82
80	0.42	0.25	0.67
90	0.00	0.00	0.00

0.87 and 0.85, respectively. For direct radiation, the transmittance varies markedly with the angle of incidence, as shown in Table 4, which gives transmittances for single and double glazing using double-strength clear window glass.

The 4% reflectance from each glass/air interface is the most important factor in reducing transmission, although a gain of about 3% in transmittance can be obtained by using water-white glass. Antireflective coatings and surface texture can also improve transmission significantly. The effect of dirt and dust on collector glazing may be quite small, and the cleansing effect of an occasional rainfall is usually adequate to maintain the transmittance within 2 to 4% of its maximum.

The glazing should admit as much solar irradiation as possible and reduce upward loss of heat as much as possible. Although glass is virtually opaque to the longwave radiation emitted by collector plates, absorption of that radiation causes an increase in the glass temperature and a loss of heat to the surrounding atmosphere by radiation and convection. This type of heat loss can be reduced by using an infrared-reflective coating on the underside of the glass; however, such coatings are expensive and reduce the effective solar transmittance of the glass by as much as 10%.

In addition to serving as a heat trap by admitting shortwave solar radiation and retaining longwave thermal radiation, the glazing also reduces heat loss by convection. The insulating effect of the glazing is enhanced by using several sheets of glass, or glass plus plastic. Loss from the back of the plate rarely exceeds 10% of the upward loss.

Collector Plates

The collector plate absorbs as much of the irradiation as possible through the glazing, while losing as little heat as possible up to the atmosphere and down through the back of the casing. The collector plates transfer retained heat to the transport fluid. The absorptance of the collector surface for shortwave solar radiation depends on the nature and color of the coating and on the incident angle, as shown in Table 4 for a typical flat black paint.

By suitable electrolytic or chemical treatments, selective surfaces can be produced with high values of solar radiation absorptance α and low values of longwave emittance e. Essentially, typical selective surfaces consist of a thin upper layer, which is highly absorbent to shortwave solar radiation but relatively transparent to longwave thermal radiation, deposited on a substrate that has a high reflectance and a low emittance for longwave radiation. Selective surfaces are particularly important when the collector surface temperature is much higher than the ambient air temperature.

For fluid-heating collectors, passages must be integral with or firmly bonded to the absorber plate. A major problem is obtaining a good thermal bond between tubes and absorber plates without incurring excessive costs for labor or materials. Materials most frequently used for collector plates are copper, aluminum, and steel.

UV-resistant plastic extrusions are used for low-temperature application. If the entire collector area is in contact with the heat transfer fluid, the material's thermal conductance is not important.

Whillier (1964) concluded that steel tubes are as effective as copper if the bond conductance between tube and plate is good. Potential corrosion problems should be considered for any metals. Bond conductance can range from 1000 Btu/h·ft^2·°F for a securely soldered or brazed tube, to 3 Btu/h·ft^2·°F for a poorly clamped or badly soldered tube. Plates of copper, aluminum, or stainless steel with integral tubes are among the most effective types available. Figure 9 shows a few of the solar water and air heaters that have been used with varying degrees of success.

Concentrating Collectors

Temperatures far above those attainable by flat-plate collectors can be reached if a large amount of solar radiation is concentrated on a relatively small collection area. Simple **reflectors** can markedly increase the amount of direct radiation reaching a collector, as shown in Figure 10A.

Because of the apparent movement of the sun across the sky, conventional concentrating collectors must follow the sun's daily motion. There are two methods by which the sun's motion can be readily tracked. The altazimuth method requires the tracking device to turn in both altitude and azimuth; when performed properly, this method enables the concentrator to follow the sun exactly. **Paraboloidal solar furnaces** (Figure 10B) generally use this system. The polar, or equatorial, mounting points the axis of rotation at the North Star, tilted upward at the angle of the local latitude. By rotating the collector 15° per hour, it follows the sun perfectly (on March 21 and September 21). If the collector surface or aperture must be kept normal to the solar rays, a second motion is needed to correct for the change in the solar declination. This motion is not essential for most solar collectors.

The maximum variation in the angle of incidence for a collector on a polar mount will be ±23.5° on June 21 and December 21; the incident angle correction would then be cos 23.5° = 0.917.

Horizontal reflective parabolic troughs, oriented east and west (Figure 10C), require continuous adjustment to compensate for the changes in the sun's declination. There is inevitably some morning and afternoon shading of the reflecting surface if the concentrator has opaque end panels. The necessity of moving the concentrator to accommodate the changing solar declination can be reduced by moving the absorber or by using a trough with two sections of a parabola facing each other, as shown in Figure 10D. Known as a **compound parabolic concentrator (CPC)**, this design can accept incoming radiation over a relatively wide range of angles. By using multiple internal reflections, any radiation that is accepted finds its way to the absorber surface located at the bottom of the apparatus. By filling the collector shape with a highly transparent material having an index of refraction greater than 1.4, the acceptance angle can be increased. By shaping the surfaces of the array properly, total internal reflection is made to occur at the medium/air interfaces, which results in a high concentration efficiency. Known as a **dielectric compound parabolic concentrator (DCPC)**, this device has been applied to the photovoltaic generation of electricity (Cole et al. 1977).

The parabolic trough of Figure 10E can be simulated by many flat strips, each adjusted at the proper angle so that all reflect onto a common target. By supporting the strips on ribs with parabolic contours, a relatively efficient concentrator can be produced with less tooling than the complete reflective trough.

Another concept applied this segmental idea to flat and cylindrical lenses. A modification is shown in Figure 10F, in which a linear **Fresnel lens**, curved to shorten its focal distance, can concentrate a relatively large area of radiation onto an elongated receiver. Using the equatorial sun-following mounting, this type of concentrator has been used to attain temperatures well above those that can be reached with flat-plate collectors.

A. FLAT PLATE COLLECTOR WITH REFLECTIVE WINGS

B. PARABOLOIDAL CONCENTRATOR

C. PARABOLIC TROUGH

D. COMPOUND PARABOLIC CONCENTRATOR

E. FRESNEL PARABOLIC TROUGH

F. LINEAR FRESNEL CONCENTRATOR
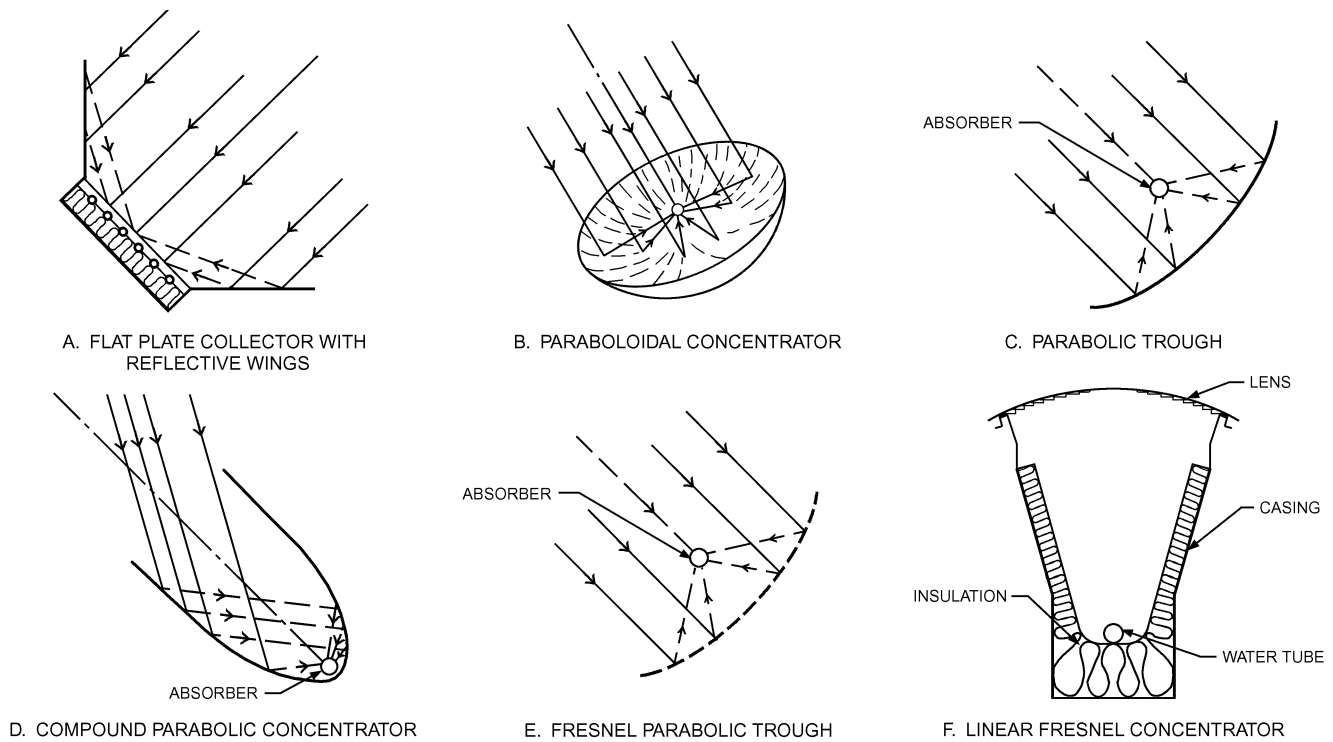
Fig. 10 Types of Concentrating Collectors

One disadvantage of concentrating collectors is that, except at low concentration ratios, they can use only the direct component of solar radiation, because the diffuse component cannot be concentrated by most types. However, an advantage of concentrating collectors is that, in summer, when the sun rises and sets well to the north of the east-west line, the sun-follower, with its axis oriented north-south, can begin to accept radiation directly from the sun long before a fixed, south-facing flat plate can receive anything other than diffuse radiation from the portion of the sky that it faces. At 40° north latitude, for example, the cumulative direct radiation available to a sun-follower on a clear day is 3180 Btu/ft^2, whereas the total radiation falling on the flat plate tilted upward at an angle equal to the latitude is only 2220 Btu/ft^2 each day. Thus, in relatively cloudless areas, the concentrating collector may capture more radiation per unit of aperture area than a flat-plate collector.

To get extremely high inputs of radiant energy, many flat mirrors, or heliostats, using altazimuth mounts, can be used to reflect their incident direct solar radiation onto a common target. Using slightly concave mirror segments on the heliostats, large amounts of thermal energy can be directed into the cavity of a steam generator to produce steam at high temperature and pressure.

Collector Performance

The performance of collectors may be analyzed by a procedure originated by Hottel and Woertz (1942) and extended by Whillier (ASHRAE 1977). The basic equation is

$$q_u = I_{t\theta}(\tau\alpha)_\theta - U_L(t_p - t_{at}) = \dot{m}c_p(t_{fe} - t_{fi})/A_{ap} \qquad (24)$$

Equation (24) also may be adapted for use with concentrating collectors:

$$q_u = I_{DN}(\tau\alpha)_\theta(\rho\Gamma) - U_L(A_{abs}/A_{ap})(t_{abs} - t_a) \qquad (25)$$

where

q_u = useful heat gained by collector per unit of aperture area, Btu/h·ft^2

$I_{t\theta}$ = total irradiation of collector, Btu/h·ft^2

I_{DN} = direct normal irradiation, Btu/h·ft^2

$(\tau\alpha)_\theta$ = transmittance τ of cover times absorptance α of plate at prevailing incident angle θ

U_L = upward heat loss coefficient, Btu/h·ft^2·°F

t_p = temperature of absorber plate, °F

t_a = temperature of atmosphere, °F

t_{abs} = temperature of absorber, °F

$\dot{m}$ = fluid flow rate, lb/h

c_p = specific heat of fluid, Btu/lb·°F

t_{fe}, t_{fi} = temperatures of fluid leaving and entering collector, °F

$\rho\Gamma$ = reflectance of concentrator surface times fraction of reflected or refracted radiation that reaches absorber

A_{abs}, A_{ap} = areas of absorber surface and of aperture that admit or receive radiation, ft^2

The total and direct normal irradiation for clear days may be found in ASHRAE *Standard* 93. The transmittance for single and double glazing and the absorptance for flat black paint may be found in Table 4 for incident angles from 0 to 90°. These values, and the products of τ and α, are also shown in Figure 11. The solar-optical properties of the glazing and absorber plate change little until θ exceeds 30°, but, because all values reach zero when $\theta = 90°$, they drop off rapidly for values of θ beyond 40°.

For nonselective absorber plates, U_L varies with the temperature of the plate and the ambient air, as shown in Figure 12. For selective surfaces, which effect major reductions in the emittance of the absorber plate, U_L will be much lower than the values shown in Figure 12. Manufacturers of such surfaces should be asked for values applicable to their products, or test results that give the necessary information should be consulted.

Example 5. A flat-plate collector is operating in Denver, latitude = 40° north, on July 21 at noon solar time. The atmospheric temperature is 85°F, and the average temperature of the absorber plate is 140°F. The
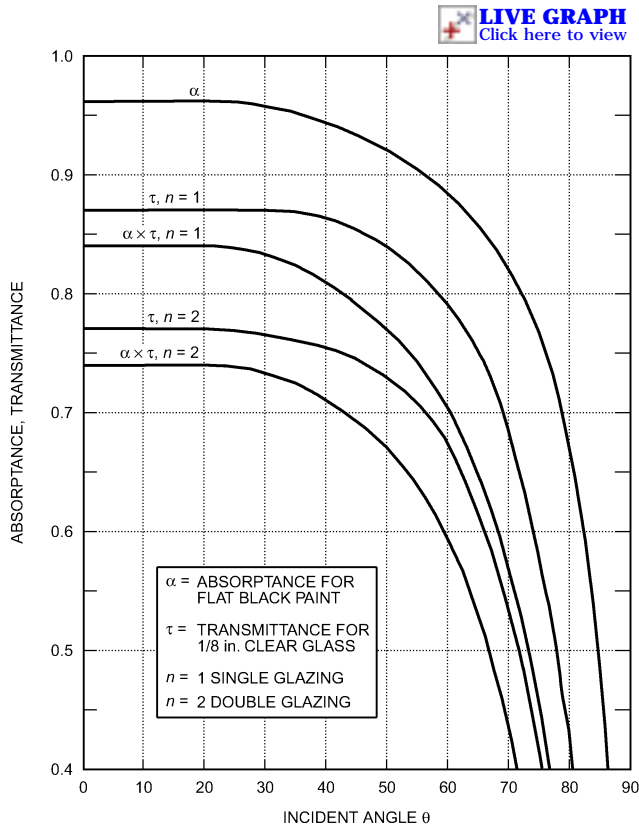
Fig. 11   Variation of Absorptance and Transmittance with Incident Angle

Note: Absorber plate is coated with nonselective flat black paint.
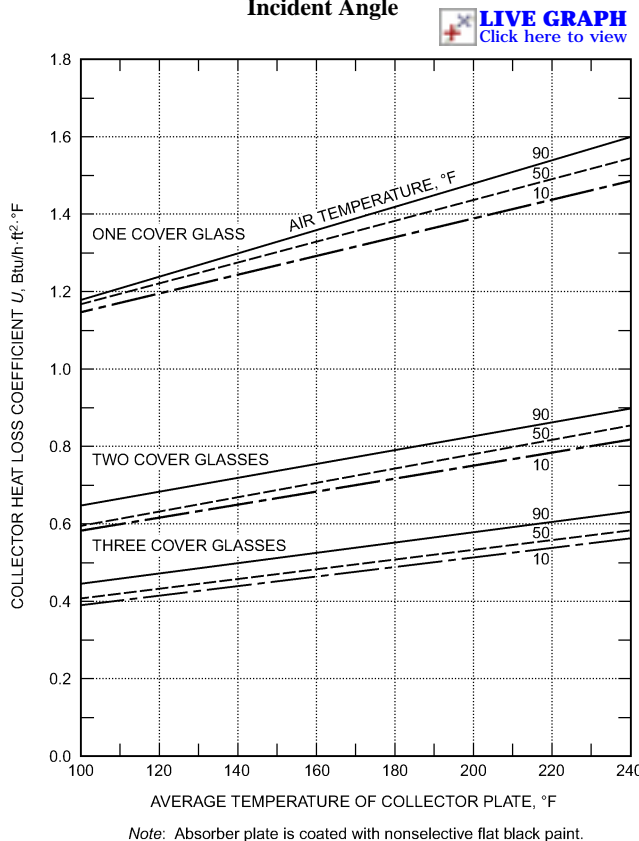
Fig. 12   Variation of Upward Heat Loss Coefficient U_L with Collector Plate Temperature and Ambient Air Temperatures for Single-, Double-, and Triple-Glazed Collectors

collector is single-glazed with flat black paint on the absorber. The collector faces south, and the tilt angle is 30° from the horizontal. Find the rate of heat collection and collector efficiency. Neglect losses from the back and sides of the collector.

Solution: From Table 2, δ = 20.6°.
From Equation (2),

$$\beta_N = 90° - 40° + 20.6° = 70.6°$$

From Equation (3), $H = 0$; therefore from Equation (6), sin ϕ = 0 and thus, ϕ = 0°. Because the collector faces south, ψ = 0°, and γ = ϕ. Thus γ = 0°. Then Equation (8) gives

$$\begin{aligned} \cos\theta &= \cos 70.6° \cos 0° \sin 30° + \sin 70.6° \cos 30° \\ &= (0.332)(1)(0.5) + (0.943)(0.866) \\ &= 0.983 \\ \theta &= 10.6° \end{aligned}$$

From Table 1, $A = 344$ Btu/h·ft^2, $B = 0.207$, and $C = 0.136$. Using Equation (11),

$$I_{DN} = 344 e^{-0.207/\sin 70.6°} = 276 \text{ Btu/h} \cdot \text{ft}^2$$

Combining Equations (14) and (15) gives

$$I_{d\theta} = 0.136 \times 276(1 + \cos 30°)/2 = 35 \text{ Btu/h} \cdot \text{ft}^2$$

Assuming $I_r = 0$, Equation (12) gives a total solar irradiation on the collector of

$$I_{t\theta} = 276 \cos 10.6° + 35 + 0 = 306 \text{ Btu/h} \cdot \text{ft}^2$$

From Figure 11, for $n = 1$, τ = 0.87 and α = 0.96.
From Figure 12, for an absorber plate temperature of 140°F and an air temperature of 85°F, $U_L = 1.3$ Btu/h·ft^2·°F.
Then from Equation (24),

$$q_u = 306(0.87 \times 0.96) - 1.3(140 - 85) = 184 \text{ Btu/h} \cdot \text{ft}^2$$

Collector efficiency η is

$$184/306 = 0.60$$

The general expression for collector efficiency is

$$\eta = (\tau\alpha)_\theta - U_L(t_p - t_a)/I_{t\theta} \qquad (26)$$

For incident angles below about 35°, the product τα is essentially constant and Equation (26) is linear with respect to the parameter $(t_p - t_a)/I_{t\theta}$, as long as U_L remains constant.

ASHRAE (1977) suggested that an additional term, the **collector heat removal factor F_R**, be introduced to allow use of the fluid inlet temperature in Equations (24) and (26):

$$q_u = F_R\left[I_{t\theta}(\tau\alpha)_\theta - U_L(t_{fi} - t_a)\right] \qquad (27)$$

$$\eta = F_R(\tau\alpha)_\theta - F_R U_L(t_{fi} - t_a)/I_{t\theta} \qquad (28)$$

where F_R equals the ratio of the heat actually delivered by the collector to the heat that would be delivered if the absorber were at t_{fi}. F_R is found from the results of a test performed in accordance with ASHRAE *Standard* 93. The Solar Rating and Certification Corporation (SRCC) conducts this test in the United States and publishes the results, along with day-long performance outputs. Similar organizations around the world [e.g., the International Organization for Standardization (ISO), the European Committee for Standardization (CEN), Commonwealth Scientific and Industrial Research Organization (CISRO)] provide similar test results.

The results of such a test are plotted in Figure 13. When the parameter is zero, because there is no temperature difference between fluid entering the collector and the atmosphere, the value of the *y*-intercept equals $F_R(\tau\alpha)$. The slope of the efficiency line equals
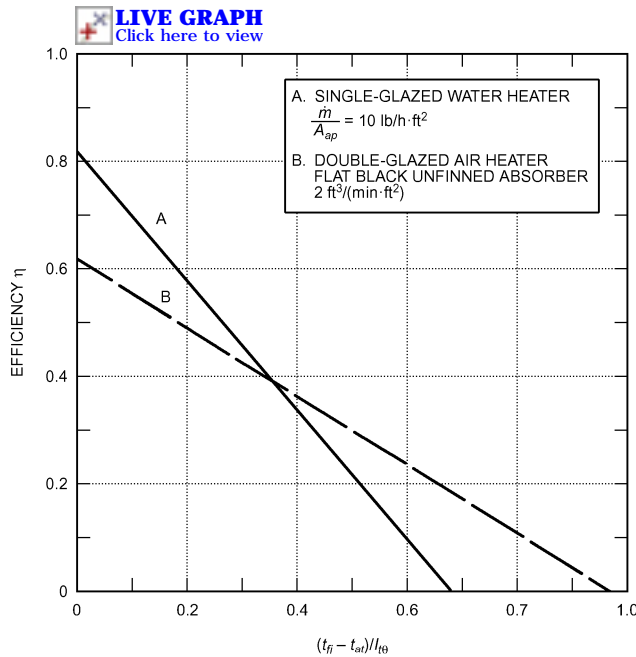
Fig. 13 Efficiency Versus $(t_{fi} - t_{at})/I_{t\theta}$ for Single-Glazed Solar Water Heater and Double-Glazed Solar Air Heater

the heat loss factor U_L multiplied by F_R. For the single-glazed, nonselective collector with the test results shown in Figure 13, the y-intercept is 0.82, and the x-intercept is 0.69°F·ft²·h/Btu. This collector used high-transmittance single glazing, $\tau = 0.91$, and black paint with an absorptance of 0.97, so Equation (28) gives $F_R = 0.82/(0.91 \times 0.97) = 0.93$.

Assuming that the relationship between η and the parameter is actually linear, as shown, then the slope is $-0.82/0.69 = -1.19$; thus $U_L = 1.19/F_R = 1.19/0.93 = 1.28$ Btu/h·ft²·°F. The tests on which Figure 13 is based were run indoors. Wind speed and fluid velocity can affect measured efficiency.

Figure 13 also shows the efficiency of a double-glazed air heater with an unfinned absorber coated with flat black paint. The y-intercept for the air heater B is considerably less than it is for water heater A because (1) transmittance of the double glazing used in B is lower than the transmittance of the single glazing used in A and (2) F_R is lower for B than for A because of the lower heat transfer coefficient between air and the unfinned metal absorber.

The x-intercept for air heater B is greater than it is for the water heater A because the upward loss coefficient U_L is much lower for the double-glazed air heater than for the single-glazed water heater. The data for both A and B were taken at near-normal incidence with high values of $I_{t\theta}$. For Example 5, using a single-glazed water heater, the value of the parameter would be close to $(140 - 85)/306 = 0.18$°F·ft²·h/Btu, and the expected efficiency, 0.60, agrees closely with the test results.

As ASHRAE *Standard* 93 shows, the incident angles encountered with south-facing tilted collectors vary widely throughout the year. Considering a surface located at 40° north latitude with a tilt angle $\Sigma = 40°$, the incident angle θ will depend on the time of day and the declination δ. On December 21, $\delta = 23.456°$; at 4 h before and after solar noon, the incident angle is 62.7°, and remains close to this value for the same solar time throughout the year. Total irradiation at these conditions varies from a low of 45 Btu/h·ft² on December 21 to approximately 140 Btu/h·ft² throughout most of the other months.

When irradiation is below about 100 Btu/h·ft², losses from the collector may exceed the heat that can be absorbed. This situation

varies with the temperature difference between the collector inlet temperature and the ambient air, as suggested by Equation (27).

When the incident angle rises above 30°, the product of the glazing's transmittance and the collector plate's absorptance begins to diminish; thus, heat absorbed also drops. Losses from the collector are generally higher as time moves farther from solar noon, and consequently efficiency also drops. Thus, the daylong efficiency is lower than the near-noon performance. During early afternoon, efficiency is slightly higher than at the comparable morning time, because the ambient air temperature is lower in the morning than in the afternoon.

ASHRAE *Standard* 93 describes the **incident angle modifier**, which may be found by tests run when the incident angle is set at 30, 45, and 60°. Simon (1976) showed that for many flat-plate collectors, the incident angle modifier is a linear function of the quantity $(1/\cos \theta - 1)$. For evacuated tubular collectors, the incident angle modifier may grow with rising values of θ.

ASHRAE *Standard* 93 specifies that efficiency be reported in terms of the gross collector area A_g rather than the aperture area A_{ap}. The reported efficiency will be lower than that given by Equation (28), but the total energy collected is not changed by this simplification:

$$\eta_g = \frac{\eta_{ap}A_{ap}}{A_g} \qquad (29)$$

COMPONENTS

This section describes the major components involved in the collection, storage, transportation, control, and distribution of solar heat for a domestic hot-water system.

Collectors. Flat-plate collectors are most commonly used for water heating because of the year-round load requiring temperatures of 80 to 180°F. For discussions of other collectors and applications, see ASHRAE *Standard* 93, Chapter 33 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*, and previous sections of this chapter. Collectors must withstand extreme weather (e.g., freezing, stagnation, high winds), as well as system pressures.

Heat Transfer Fluids. Heat transfer fluids transport heat from the solar collectors to the domestic water. The potential safety problems that exist in this transfer are both chemical and mechanical and apply primarily to systems in which a heat exchanger interface exists with the potable water supply. Both the chemical compositions of the heat transfer fluids (pH, toxicity, and chemical durability) and their mechanical properties (specific heat and viscosity) must be considered.

Except in unusual cases, or when potable water is being circulated, the energy transport fluid is nonpotable and has the potential for contaminating potable water. Even potable or nontoxic fluids in closed circuits are likely to become nonpotable because of contamination from metal piping, solder joints, and packing, or by the inadvertent installation of a toxic fluid at a later date.

Thermal Energy Storage. Heat collected by solar domestic and service water heaters is virtually always stored as a liquid in tanks. Storage tanks and bins should be well insulated. In domestic hot-water systems, heat is usually stored in one or two tanks. The hot-water outlet is at the top of the tank, and cold water enters the tank through a dip tube that extends down to within 4 to 6 in. of the tank bottom. The outlet on the tank to the collector loop should be approximately 4 in. above the tank bottom to prevent scale deposits from being drawn into the collectors. Water from the collector array returns to the middle to lower portion of the storage tank. This plumbing arrangement may take advantage of thermal stratification, depending on the delivery temperature from the collectors and the flow rate through the storage tank.

Single-tank electric auxiliary systems often incorporate storage and auxiliary heating in the same vessel. Conventional electric

water heaters commonly have two heating elements: one near the top and one near the bottom. If a dual-element tank is used in a solar energy system, the bottom element should be disconnected and the top left functional to take advantage of fluid stratification. Standard gas- and oil-fired water heaters should not be used in single-tank arrangements. In gas and oil water heaters, heat is added to the bottom of the tanks, which reduces both stratification and collection efficiency in single-tank systems.

Dual-tank systems often use the solar domestic hot-water storage tank as a preheat tank. The second tank is normally a conventional domestic hot-water tank containing the auxiliary heat source. Multiple tanks are sometimes used in large institutions, where they operate similarly to dual-tank heaters. Although using two tanks may increase collector efficiency and the solar fraction, it increases tank heat losses. The water inlet is usually a dip tube that extends near the bottom of the tank.

Estimates for sizing storage tanks usually range from 1 to 2.5 gal per square foot of solar collector area. The estimate used most often is 1.8 gal per square foot of collector area, which usually provides enough heat for a sunless period of about a day. Storage volume should be analyzed and sized according to the project water requirements and draw schedule; however, solar applications typically require larger-than-normal tanks, typically the equivalent of the average daily load.

Heat Exchangers. Indirect solar water heaters require one or more heat exchangers. The potential exists for contamination in the transfer of heat energy from solar collectors to potable hot water. Heat exchangers influence the effectiveness of energy collected to heat domestic water. They also separate and protect the potable water supply from contamination when nonpotable heat transfer fluids are used. For this reason, various codes regulate the need for and design of heat exchangers.

Heat exchanger selection should consider the following:

- Heat exchange effectiveness
- Pressure drop, operating power, and flow rate
- Design pressure, configuration, size, materials, and location
- Cost and availability
- Reliable protection of the potable water supply from contamination by the heat transfer fluid
- Leak detection, inspection, and maintainability
- Material compatibility with other elements (e.g., metals and fluids)
- Thermal compatibility with design parameters such as operating temperature, and fluid thermal properties

Heat exchanger selection depends on the characteristics of the fluids that pass through the heat exchanger and the properties of the exchanger itself. Fluid characteristics to consider are fluid type, specific heat, mass flow rate, and hot- and cold-fluid inlet and outlet temperatures. Physical properties of the heat exchanger to consider are the overall heat transfer coefficient of the heat exchanger and the heat transfer surface area.

For most solar domestic hot-water designs, only the hot and cold inlet temperatures are known; the other temperatures must be calculated using the physical properties of the heat exchanger. Two quantities that are useful in determining the heat transfer in a heat exchanger and the performance characteristics of a collector when it is combined with a given heat exchanger are the (1) fluid capacitance rate, which is the product of the mass flow rate and specific heat of fluid passing through the heat exchanger, and (2) heat exchanger effectiveness, which relates the capacitance rate of the two fluids to the fluid inlet and outlet temperatures. The effectiveness is equal to the ratio of the actual heat transfer rate to the maximum heat transfer rate theoretically possible. Generally, a heat exchanger effectiveness of 0.4 or greater is desired.

Expansion Tanks. An indirect solar water heater operating in a closed collector loop requires an expansion tank to prevent excessive pressure. Fluid in solar collectors under stagnation conditions can boil, causing excessive pressure to develop in the collector loop, and expansion tanks must be sized for this condition. Expansion tank sizing formulas for closed-loop hydronic systems, found in Chapter 12 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*, may be used for solar heater expansion tank sizing, but the expression for volume change due to temperature increase should be replaced with the total volume of fluid in the solar collectors and of any piping located above the collectors, if significant. This sizing method provides a passive means for eliminating fluid loss due to overtemperature or stagnation, common problems in closed-loop solar systems. This results in a larger expansion tank than typically found in hydronic systems, but the increase in cost is small compared to the savings in fluid replacement and maintenance costs (Lister and Newell 1989).

Pumps. Pumps circulate heat transfer liquid through collectors and heat exchangers. In solar domestic hot-water heaters, the pump is usually a centrifugal circulator driven by a motor of less than 300 W. The flow rate for collectors generally ranges from 0.015 to 0.04 gpm/ft^2. Pumps used in drainback systems must provide pressure to overcome friction and to lift the fluid to the collectors.

Piping. Piping can be plastic, copper, galvanized steel, or stainless steel. The most widely used is nonlead, sweat-soldered L-type copper tubing. M-type copper is also acceptable if permitted by local building codes. If water/glycol is the heat transfer fluid, galvanized pipes or tanks must not be used because unfavorable chemical reactions will occur; copper piping is recommended instead. Also, if glycol solutions or silicone fluids are used, they may leak through joints where water would not. Piping should be compatible with the collector fluid passage material; for example, copper or plastic piping should be used with collectors having copper fluid passages.

Piping that carries potable water can be plastic, copper, galvanized steel, or stainless steel. In indirect systems, corrosion inhibitors must be checked and adjusted no less than annually, preferably every three months. Inhibitors should also be checked if the system overheats during stagnation conditions. If dissimilar metals are joined, dielectric or nonmetallic couplings should be used. The best protection is sacrificial anodes or getters in the fluid stream. Their location depends on the material to be protected, anode material, and electrical conductivity of the heat transfer fluid. Sacrificial anodes of magnesium, zinc, or aluminum are often used to reduce corrosion in storage tanks. Because many possibilities exist, each combination must be evaluated. A copper-aluminum or copper-galvanized steel joint is unacceptable because of severe galvanic corrosion. Aluminum, copper, and iron have a greater potential for corrosion.

Elimination of air, pipe expansion, and piping slope must be considered to avoid possible failures. Collector pipes (particularly manifolds) should be designed to allow expansion from stagnation temperature to extreme cold weather temperature. Expansion control can be achieved with offset elbows in piping, hoses, or expansion couplings. Expansion loops should be avoided unless they are installed horizontally, particularly in systems that must drain for freeze protection. The collector array piping should slope 0.06 in. per foot for drainage (DOE 1978a).

Air can be eliminated by placing air vents at all piping high points and by air purging during filling. Flow control, isolation, and other valves in the collector piping must be chosen carefully so that these components do not restrict drainage significantly or back up water behind them. The collectors must drain completely.

Valves and Gages. Valves in solar domestic hot-water systems must be located to ensure system efficiency, satisfactory performance, and the safety of equipment and personnel. Drain valves must be ball-type; gate valves may be used if the stem is installed horizontally. Check valves or other valves used for freeze protection or for reverse thermosiphoning must be reliable to avoid significant damage.

Auxiliary Heat Sources. On sunny days, a typical solar energy system should supply water at a predetermined temperature, and the

solar storage tank should be large enough to hold sufficient water for a day or two. Because of the intermittent nature of solar radiation, an auxiliary heater must be installed to handle hot-water requirements. If a utility is the source of auxiliary energy, operation of the auxiliary heater can be timed to take advantage of off-peak utility rates. The auxiliary heater should be carefully integrated with the solar energy heater to obtain maximum solar energy use. For example, the auxiliary heater should not destroy any stratification that may exist in the solar-heated storage tank, which would reduce collector efficiency.

Ductwork, particularly in systems with air-type collectors, must be sealed carefully to avoid leakage in duct seams, damper shafts, collectors, and heat exchangers. Ducts should be sized using conventional air duct design methods.

Control. Controls regulate solar energy collection by controlling fluid circulation, activate system protection against freezing and overheating, and initiate auxiliary heating when it is required. The three major control components are sensors, controllers, and actuators. Sensors detect conditions or measure quantities, such as temperature. Controllers receive output from the sensors, select a course of action, and signal a component to adjust the condition. Actuators, such as pumps, valves, dampers, and fans, execute controller commands and regulate the system.

Temperature sensors measure the temperature of the absorber plate near the collector outlet and near the bottom of the storage tank. The sensors send signals to a controller, such as a differential temperature thermostat, for interpretation.

The differential thermostat compares signals from the sensors with adjustable set points for high and low temperature differentials. The controller performs different functions, depending on which set points are met. In liquid systems, when the temperature difference between the collector and storage reaches a high set point, usually 12 to 15°F, the pump starts, automatic valves are activated, and circulation begins. When the temperature difference reaches a low set point, usually 4°F, the pump is shut off and the valves are deenergized and returned to their normal positions. To restart the system, the differential temperature set point must again be met. If the system has either freeze or overheat protection, the controller opens or closes valves or dampers and starts or stops pumps or fans to protect the system when its sensors detect conditions indicating that either freezing or overheating is about to occur.

Sensors must be selected to withstand high temperature, such as may occur during collector stagnation. Collector loop sensors should be located as close as possible to the outlet of the collectors, either in a pipe above the collector, on a pipe near the collector, or in the collector outlet passage.

The storage temperature sensor should be near the bottom of the storage tank to detect the temperature of fluid before it is pumped to the collector or heat exchanger. Storage fluid is usually coldest at that location because of thermal stratification and the location of the makeup water supply. The sensor should be either securely attached to the tank and well insulated, or immersed inside the tank near the collector supply.

The freeze protection sensor, if required, should be located so that it will detect the coldest liquid temperature when the collector is shut down. Common locations are the back of the absorber plate at the bottom of the collector, the collector intake or return manifolds, or the center of the absorber plate. The center absorber plate location is recommended because reradiation to the night sky will freeze the collector heat transfer fluid, even though the ambient temperature is above freezing. Some systems, such as the recirculation system, have two sensors for freeze protection; others, such as the draindown, use only one.

Control of on/off temperature differentials affects system efficiency. If the differential is too high, the collector starts later than it should; if it is too low, the collector starts too soon. The turn-on differential for liquid systems usually ranges from 10 to 30°F and is commonly lower in warmer climates and higher in cold climates. For air systems, the range is usually 25 to 45°F.

The turn-off temperature differential is more difficult to estimate. Selection depends on a comparison between the value of the energy collected and the cost of collecting it. It varies with individual systems, but a value of 4°F is typical and generally the fixed default value in the control.

Water temperature in the collector loop depends on ambient temperature, solar radiation, radiation from the collector to the night sky, and collector loop insulation. Freeze protection sensors should be set to detect 40°F.

Sensors are important but often overlooked control components. They must be selected and installed properly because no control can produce accurate outputs from unreliable sensor inputs. Sensors are used in conjunction with a differential temperature controller and are usually supplied by the controller manufacturer. Sensors must survive the anticipated operating conditions without physical damage or loss of accuracy. Low-voltage sensor circuits must be located away from high-voltage lines to avoid electromagnetic interference. Sensors attached to collectors should be able to withstand the stagnation temperature.

Sensor calibration, which is often overlooked by installers and maintenance personnel, is critical to system performance; a routine calibration maintenance schedule is essential.

Another control option is to use a photovoltaic (PV) panel that powers a pump. A properly sized and oriented PV panel converts sunlight into electricity to run a small circulating pump. No additional sensing is required because the PV panel and pump output increase with sunlight intensity and stop when no sunlight (collector energy) is available. Cromer (1984) showed that, with proper matching of pump and PV electrical characteristics, PV panel sizes as low as 5 W per 40 ft^2 of thermal panel may be used successfully. Difficulty with late starting and running too long in the afternoon can be alleviated by tilting the PV panel slightly to the east during commissioning of the installed system.

WATER HEATING

A solar water heater includes a solar collector that absorbs solar radiation and converts it to heat, which is then absorbed by a heat transfer fluid (water, a nonfreezing liquid, or air) that passes through the collector. The heat transfer fluid's heat is stored or used directly.

Portions of the solar energy system are exposed to the weather, so they must be protected from freezing. The system must also be protected from overheating caused by high insolation levels during periods of low energy demand.

In solar water heating, water is heated directly in the collector or indirectly by a heat transfer fluid that is heated in the collector, passes through a heat exchanger, and transfers its heat to the domestic or service water. The heat transfer fluid is transported by either natural or forced circulation. Natural circulation occurs by natural convection (thermosiphoning), whereas forced circulation uses pumps or fans. Except for thermosiphon systems, which need no control, solar domestic and service water heaters are controlled by differential thermostats.

Five types of solar energy systems are used to heat domestic and service hot water: thermosiphon, direct circulation, indirect, integral collector storage, and site built. Recirculation and draindown are two methods used to protect direct solar water heaters from freezing.

Thermosiphon Systems

Thermosiphon systems (Figure 14) heat potable water or a heat transfer fluid and rely on natural convection to transport it from the collector to storage. For direct systems, pressure-reducing valves are required when the city water pressure is greater than the working pressure of the collectors. In a thermosiphon system, the storage tank must be elevated above the collectors, which sometimes

requires designing the upper level floor and ceiling joists to bear this additional load. Extremely hard or acidic water can cause scale deposits that clog or corrode the absorber fluid passages. Thermosiphon flow is induced whenever there is sufficient sunshine, so these systems do not need pumps.

Direct-Circulation Systems

A direct-circulation system (Figure 15) pumps potable water from storage to the collectors when there is enough solar energy available to warm it. It then returns the heated water to the storage tank until it is needed. Collectors can be mounted either above or below the storage tank. Direct-circulation systems are only feasible in areas where freezing is infrequent. Freeze protection is provided either by recirculating warm water from the storage tank or by flushing the collectors with cold water. Direct water-heating systems should not be used in areas where the water is extremely hard or acidic because scale deposits may clog or corrode the absorber fluid passages, rendering the system inoperable.

Direct-circulation systems are exposed to city water line pressures and must withstand pressures as required by local codes. Pressure-reducing valves and pressure-relief valves are required when city water pressure is greater than the working pressure of the collectors. Direct-circulation systems often use a single storage tank
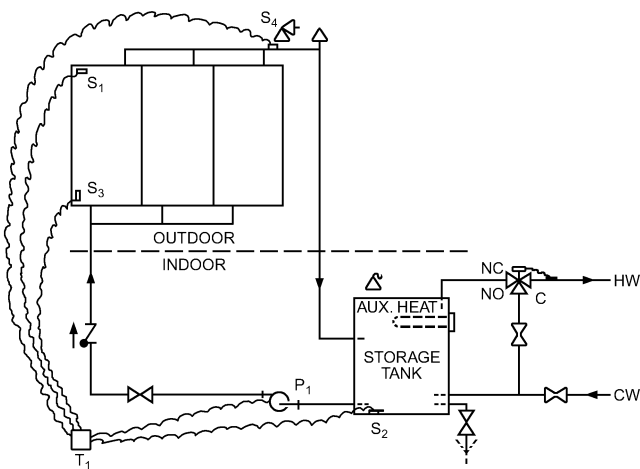
for both solar energy storage and the auxiliary water heater, but two-tank storage systems can be used.

Draindown Systems. Draindown systems (Figure 16) are direct-circulation water-heating systems in which potable water is pumped from storage to the collector array where it is heated. Circulation continues until usable solar heat is no longer available. When a freezing condition is anticipated or a power outage occurs, the system drains automatically by isolating the collector array and exterior piping from the city water pressure and using one or more valves for draining. Solar collectors and associated piping must be carefully sloped to drain the collector's exterior piping.

Indirect Water-Heating Systems

Indirect water-heating systems (Figure 17) circulate a freeze-protected heat transfer fluid through the closed collector loop to a heat exchanger, where its heat is transferred to the potable water. The most commonly used heat transfer fluids are water/ethylene glycol and water/propylene glycol solutions, although other heat transfer fluids such as silicone oils, hydrocarbons, and refrigerants can also be used (ASHRAE 1983). These fluids are nonpotable, sometimes toxic, and normally require double-wall heat exchangers. The double-wall heat exchanger can be located inside the storage tank, or an external heat exchanger can be used. The collector loop is closed and therefore requires an expansion tank and a pressure-relief valve. A one- or two-tank storage can be used. Additional overtemperature

Fig. 14 Thermosiphon System
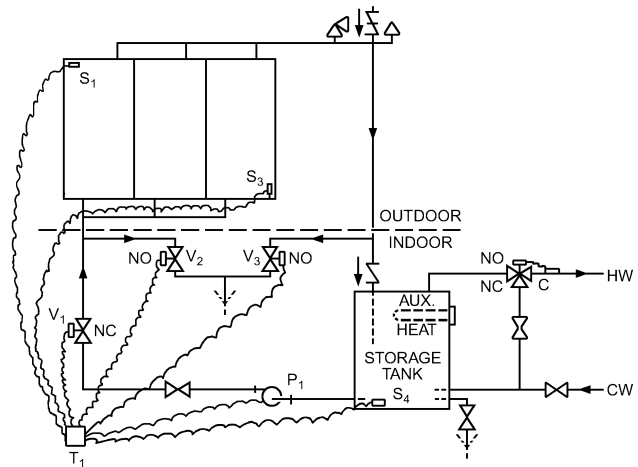
Fig. 16 Draindown System

Fig. 15 Direct Circulation System
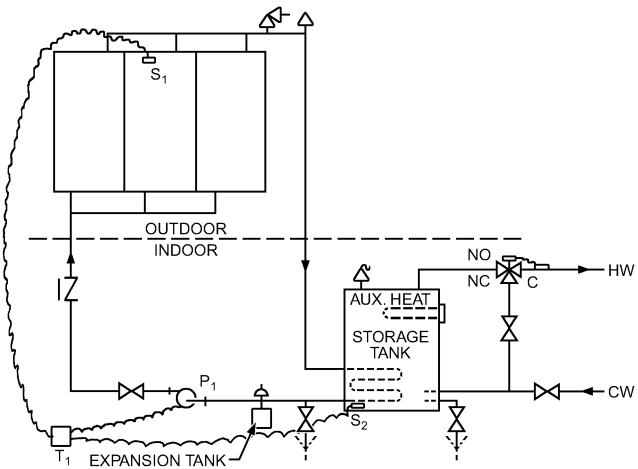
Fig. 17 Indirect Water Heating

protection may be needed to prevent the collector fluid from decomposing or becoming corrosive.

Designers should avoid automatic water makeup in systems using water/antifreeze solutions because a significant leak may raise the freezing temperature of the solution above the ambient temperature, causing the collector array and exterior piping to freeze. Also, antifreeze systems with large collector arrays and long pipe runs may need a time-delayed bypass loop around the heat exchanger to avoid freezing the heat exchanger on start-up.

Drainback Systems. Drainback systems are generally indirect water-heating systems that circulate treated or untreated water through the closed collector loop to a heat exchanger, where its heat is transferred to the potable water. Circulation continues until usable energy is no longer available. When the pump stops, the collector fluid drains by gravity to a storage or tank. In a pressurized system, the tank also serves as an expansion tank, so it must have a temperature- and pressure-relief valve to protect against excessive pressure. In an unpressurized system (Figure 18), the tank is open and vented to the atmosphere.

The collector loop is isolated from the potable water, so valves are not needed to actuate draining, and scaling is not a problem. The collector array and exterior piping must be sloped to drain completely, and the pumping pressure must be sufficient to lift water to the top of the collector array.

Integral Collector Storage Systems

Integral collector storage (ICS) systems use hot-water storage as part of the collector. Some types use the surface of a single tank as the absorber, and others use multiple long, thin tanks placed side by side horizontally to form the absorber surface. In this type of ICS, hot water is drawn from the top tank, and cold replacement water enters the bottom tank. Because of the greater nighttime heat loss from ICS systems, they are typically less efficient than pumped systems, and use of selective surfaces is strongly recommended. ICS systems are normally installed as a solar preheater without pumps or controllers. Flow through the ICS system occurs on demand, as hot water flows from the collector to a hot-water auxiliary tank in the structure.

SRCC provides annual performance results for these various types of systems at www.solar-rating.org.

Site-Built Systems

Site-built, large-volume solar air-, or water-heating equipment is used in commercial and industrial applications. These site-built systems are based on a transpired solar collector for air heating and shallow solar pond technologies.

Transpired Solar Collector. This collector preheats outdoor air by drawing it through small holes in a metal panel. It is typically installed on south-facing walls and is designed to heat outdoor air for building ventilation or process applications (Kutscher 1996). The prefabricated panel, made of dark metal with thousands of small holes, efficiently heats and captures fresh air by drawing it through a perforated adsorber, eliminating the cost and the reflection losses associated with a glazing. The sun heats the metal panel, which in turn heats a boundary layer of air on its surface. Air is heated as it is drawn through the small holes into a ventilation system for delivery as ventilation air, for crop drying, or other process applications.
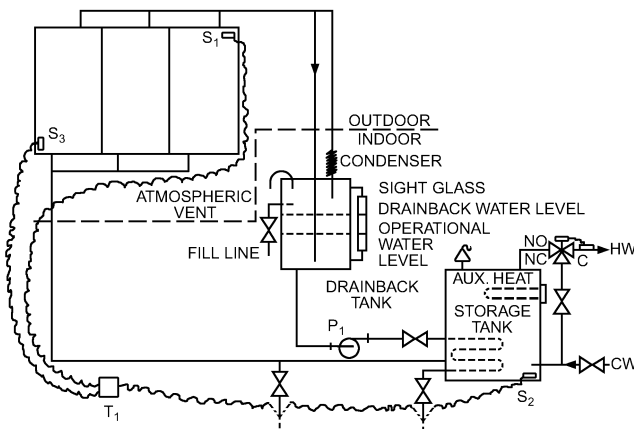
Shallow Solar Pond. The shallow solar pond (SSP) is a large-scale ICS solar water heater (Figure 19) capable of providing more than 5000 gal of hot water per day for commercial and industrial use. These ponds are built in standard modules and tied together to supply the required load. The SSP module can be ground mounted or installed on a roof. It is typically 16 ft wide and up to 200 ft long. The module contains one or two flat water bags similar to a water bed. The bags rest on a layer of insulation inside concrete or fiberglass curbs. The bag is protected against damage and heat loss by greenhouse glazing. A typical pond filled to a 4 in. depth holds approximately 6000 gal of water.

Pool Heaters

Solar pool heaters do not require a separate storage tank, because the pool itself serves as storage. In most cases, the pool's filtration pump forces the water through the solar panels or plastic pipes. In some retrofit applications, a larger pump may be required to handle the needs of the solar heater, or a small pump may be added to boost pool water to the solar collectors.

Automatic control may be used to direct the flow of filtered water to the collectors when solar heat is available; this may also be accomplished manually. Normally, solar heaters are designed to drain down into the pool when the pump is turned off; this provides the collectors with freeze protection.

Four primary types of collector designs are used for swimming pool heat: (1) rigid black plastic panels (polypropylene), usually 4 by 10 ft or 4 by 8 ft; (2) tube-on-sheet panels, which usually have a metal deck (copper or aluminum) with copper water tubes; (3) an ethylene-propylene diene monomer (or ethylene-propylene terpolymer) (EPDM) rubber mat, extruded with water passages running its length; and (4) arrays of black plastic pipe, usually 1.5 in. diameter acrylonitrile butadiene styrene (ABS) plastic (Root et al. 1985).

Hot-Water Recirculation

Domestic hot-water (DHW) recirculation systems (Figures 20 and 21), which continuously circulate domestic hot water throughout a building, are found in motels, hotels, hospitals, dormitories, office buildings, and other commercial buildings. Recirculation heat losses in these systems are usually a significant part of the total water-heating load. In Figures 20 and 21, the three-way valve prevents heated water from returning to the solar storage tank when the return temperature is greater than the solar tank temperature. This

Fig. 18   Drainback System
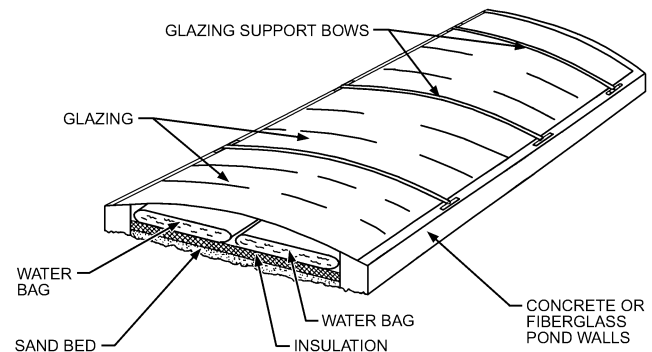
Fig. 19   Shallow Solar Pond
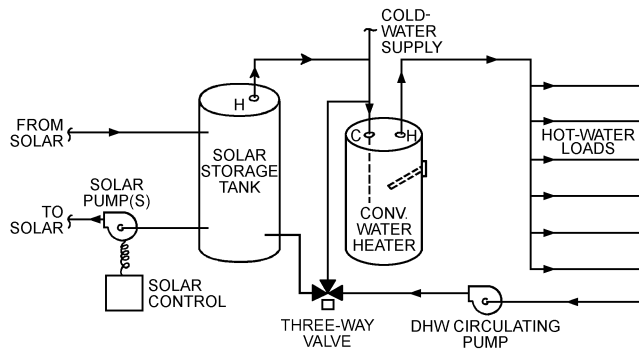
Fig. 20   DHW Recirculation System
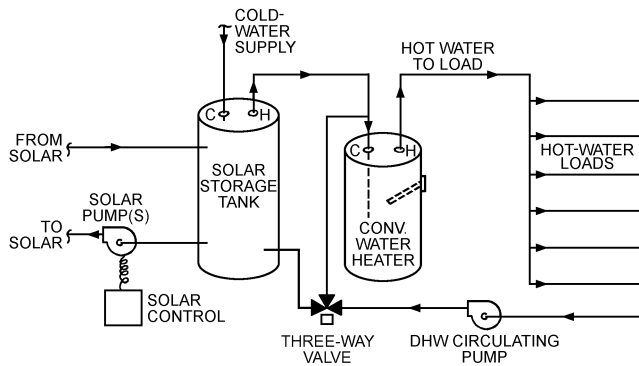
Fig. 21   DHW Recirculation System with Makeup Preheat

ensures that heated water is used only when it is hot enough and prevents heating of the solar tank by the conventional heater. Using cycle-timer to control the DHW circulating pump that is synchronized with the building hot-water consumption profile can also help reduce circulation losses.

SOLAR HEATING AND COOLING SYSTEMS

The components and subsystems discussed previously may be combined to create a wide variety of solar heating and cooling systems. These systems fall into two principal categories: passive and active.

Passive solar systems require little, if any, nonrenewable energy to make them function (Yellott 1977; Yellott et al. 1976). Every building is passive in the sense that the sun tends to warm it by day, and it loses heat at night. Passive systems incorporate solar collection, storage, and distribution into the architectural design of the building and make minimal or no use of fans to deliver the collected energy to the structure. Passive solar heating, cooling, and lighting design must consider the building envelope and its orientation, the thermal storage mass, and window configuration and design. ASHRAE (1984), DOE (1980/1982), LBL (1981), and Mazria (1979) give estimates of energy savings resulting from the application of passive solar design concepts.

Active solar systems use either liquid or air as the collector fluid. Active systems must have a continuous availability of nonrenewable energy, generally in the form of electricity, to operate pumps and fans. A complete system includes solar collectors, energy storage devices, and pumps or fans for transferring energy to storage or to the load. The load can be space cooling, heating, or hot water. Although it is technically possible to construct a solar heating and cooling system to supply 100% of the design load, such a system would be uneconomical and oversized. The size of the solar system, and thus its ability to meet the load, is determined by life-cycle cost analysis that weighs the cost of energy saved against the amortized solar cost.

Active solar energy systems have been combined with heat pumps for water and/or space heating. The most economical arrangement in residential heating is a solar system in parallel with a heat pump, which supplies auxiliary energy when the solar source is not available. For domestic water systems requiring high water temperatures, a heat pump placed in series with the solar storage tank may be advantageous. Freeman et al. (1979) and Morehouse and Hughes (1979) present information on performance and estimated energy savings for solar-heat pumps.

Hybrid systems combine elements of both active and passive systems. They require some nonrenewable energy, but the amount is so small that they can maintain a coefficient of performance (COP) of about 50. An example of a hybrid solar energy system is a floor slab thermal storage system that reradiates heat to a load (e.g., a building conditioned space) from a thermal mass surface after having been charged using an air collection system where insulated ducts feed warm air into cavities created within the heat storage slab (Howard 1986).

Passive Systems

Passive systems may be divided into several categories. The first residence to which the name **solar house** was applied used a large expanse of south-facing glass to admit solar radiation; this is known as a **direct-gain** passive system.

Indirect-gain solar houses use the south-facing wall surface or the roof of the structure to absorb solar radiation, which causes a rise in temperature that, in turn, conveys heat into the building in several ways. This principle was applied to the pueblos and cliff dwellings of the southwestern United States. Glass has led to modern adaptations of the indirect-gain principle (Balcomb et al. 1977; Trombe et al. 1977).

By glazing a large south-facing, massive masonry wall, solar energy can be absorbed during the day, and heat conduction to the inner surface provides radiant heating at night. The wall's mass and its relatively low thermal diffusivity delay the heat's arrival at the indoor surface until it is needed. The glazing reduces heat loss from the wall back to the atmosphere and increases the system's collection efficiency.

Openings in the wall near the floor and ceiling allow convection to transfer heat to the room. Air in the space between the glass and the wall warms as soon as the sun heats the outer surface of the wall. The heated air rises and enters the building through the upper openings. Cool air flows through the lower openings, and convective heat gain can be established as long as the sun is shining.

In another indirect-gain passive system, a metal roof/ceiling supports transparent plastic bags filled with water (Hay and Yellott 1969). Movable insulation above these water-filled bags is rolled away during the winter day to allow the sun to warm the stored water. The water then transmits heat indoors by convection and radiation. The insulation remains over the water bags at night or during overcast days. During the summer, the water bags are exposed at night for cooling by (1) convection, (2) radiation, and (3) evaporation of water on the bags. The insulation covers the water bags during the day to protect them from unwanted irradiation. Pittenger et al. (1978) tested a building for which water rather than insulation was moved to provide summer cooling and winter heating.

Attached greenhouses (sunspaces) can be used as solar attachments when the orientation and other local conditions are suitable. The greenhouse can provide a buffer between the exterior wall of the building and the outdoors. During daylight, warm air from the greenhouse can be introduced into the house by natural convection or a small fan.

In most passive systems, control is accomplished by moving a component that regulates the amount of solar radiation admitted into the structure. Manually operated window shades or venetian blinds are the most widely used and simplest controls.

Passive heating and cooling systems have been effective in field demonstrations A well-designed passive-solar-heated building may provide 45 to nearly 100% of daily heat requirements. Architectural design features can dramatically reduce air-conditioning loads through heat gain avoidance techniques and natural cooling, where climatically appropriate (Howard and Pollock 1982; Howard and Saunders 1989).

Passive solar daylighting has been shown to be cost-effective, providing dual benefits: it both reduces electric power demand and lowers cooling costs in properly designed interiors and atrium spaces.

COOLING BY NOCTURNAL RADIATION AND EVAPORATION

Radiative cooling is a natural heat loss that causes formation of dew, frost, and ground fog. Because its effects are the most obvious at night, it is sometimes termed **nocturnal radiation**, although the process continues throughout the day. Thermal infrared radiation, which affects the surface temperature of a building wall or roof, may be estimated by using the **sol-air temperature** concept. Radiative cooling of window and skylight surfaces can be significant, especially under winter conditions when the dew-point temperature is low.

The most useful parameter for characterizing the radiative heat transfer between horizontal nonspectral emitting surfaces and the sky is the **sky temperature** T_{sky}. If S designates the total downward radiant heat flux emitted by the atmosphere, then T_{sky} is defined as

$$T_{sky}^4 = S/\sigma \tag{30}$$

where $\sigma = 0.1713 \times 10^{-8}$ Btu/h·ft^2·°R^4.

The sky radiance is treated as if it originates from a blackbody emitter of temperature T_{sky}. The **net radiative cooling rate R_{net}** of a horizontal surface with absolute temperature T_{rad} and a nonspectral emittance ε is then

$$R_{net} = \varepsilon\sigma(T_{rad}^4 - T_{sky}^4) \tag{31}$$

Values of ε for most nonmetallic construction materials are about 0.9.

Radiative building cooling has not been fully developed. Design methods and performance data compiled by Hay and Yellott (1969) and Marlatt et al. (1984) are available for residential roof ponds that use a sealed volume of water covered by sliding insulation panels as the combined rooftop radiator and thermal storage. Other conceptual radiative cooling designs have been proposed, but more developmental work is required (Givoni 1981; Mitchell and Biggs 1979).

The sky temperature is a function of atmospheric water vapor, the amount of cloud cover, and air temperature; the lowest sky temperatures occur under an arid, cloudless sky. The monthly average sky temperature depression, which is the average of the difference between the ambient air temperature and the sky temperature, typically lies between 9 and 43°F throughout the continental United States. Martin and Berdahl (1984) calculated this quantity using hourly weather data from 193 sites, as shown in the contour map for the month of July (Figure 22).

The sky temperature may be too high at night to effectively cool the structure. Martin and Berdahl (1984) suggest that the sky temperature should be less than 61°F to achieve reasonable cooling in July (Figure 23). In regions where sky temperatures fall below 61°F 40% or more of the month, all nighttime hours are effectively available for radiative cooling.

Clark (1981) modeled a horizontal radiator at various surface temperatures in convective contact with outdoor air for 77 U.S. locations. The average monthly cooling rates for a surface temperature of 76°F are plotted in Figure 24. If effective steps are taken to

reduce the surface convection coefficient by modifying the radiator geometry or using an infrared-transparent glazing, it may be possible to improve performance beyond these values.

Active Systems

Active systems absorb solar radiation with collectors and convey it to storage using a suitable fluid. As heat is needed, it is obtained from storage via heated air or water. Control is exercised by several types of thermostats, the first being a differential device that starts
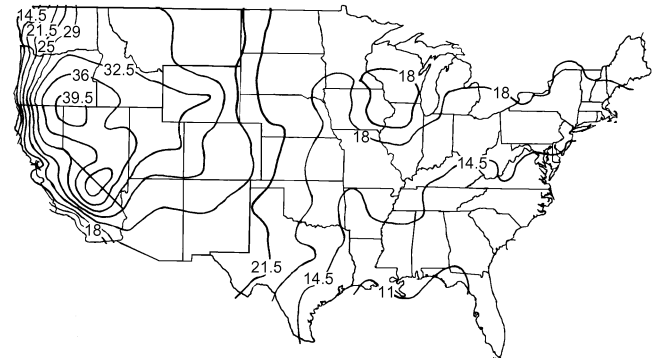
Fig. 22   Average Monthly Sky Temperature Depression ($T_{air} - T_{sky}$) for July, °F
(Adapted from Martin and Berdahl 1984)
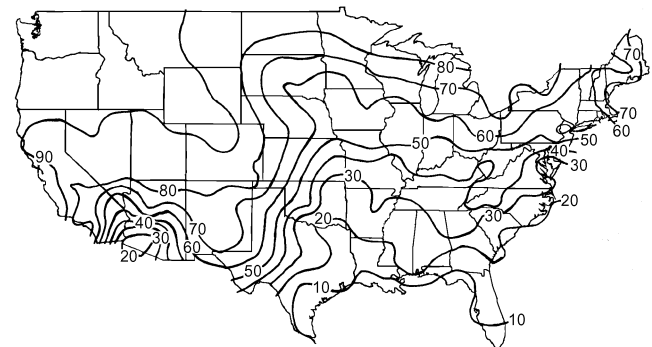
Fig. 23   Percentage of Monthly Hours when Sky Temperature Falls below 61°F
(Adapted from Martin and Berdahl 1984)

VALUES IN Btu/ft^2·day
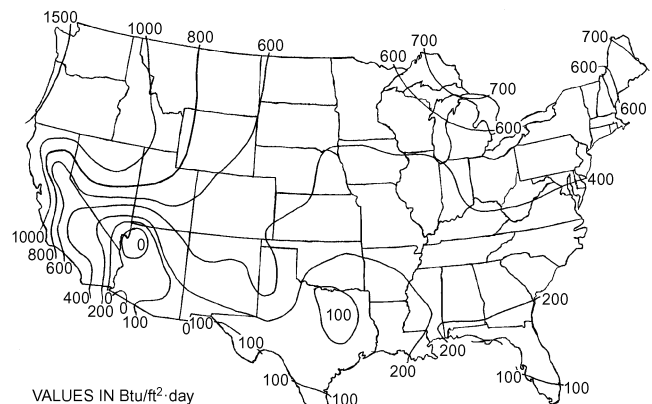
Fig. 24   July Nocturnal Net Radiative Cooling Rate from Horizontal Dry Surface at 76°F
(Adapted from Clark 1981)

the flow of fluid through the collectors when they have been sufficiently warmed by the sun. It also stops fluid flow when the collectors no longer gain heat. In locations where freezing occurs only rarely, a low-temperature sensor on the collector controls a circulating pump when freezing is impending. This process wastes some stored heat, but it prevents costly damage to the collector panels. This system is not suitable for regions where freezing temperatures persist for long periods.

The space-heating thermostat is generally the conventional double-contact type that calls for heat when the temperature in the controlled space falls to a predetermined level. If the temperature in storage is adequate to meet the heating requirement, a pump or fan is started to circulate the warm fluid. If the temperature in the storage subsystem is inadequate, the thermostat calls on the auxiliary or standby heat source.

Space Heating and Service Hot Water

Figure 25 shows one of the many systems for service hot water and space heating. In this case, a large, atmospheric pressure storage tank is used, from which water is pumped to the collectors by pump P_1 in response to the differential thermostat T_1. Drainback is used to prevent freezing, because the amount of antifreeze required would be prohibitively expensive. Service hot water is obtained by placing a heat exchanger coil in the tank near the top, where, even if stratification occurs, the hottest water will be found.

An auxiliary water heater boosts the temperature of the sun-heated water when required. Thermostat T_2 senses the indoor temperature and starts pump P_2 when heat is needed. If the water in the storage tank becomes too cool to provide enough heat, the second contact on the thermostat calls for heat from the auxiliary heater.

Standby heat becomes increasingly important as heating requirements increase. The heating load, winter availability of solar radiation, and cost and availability of the auxiliary energy must be determined. It is rarely cost-effective to do the entire heating job for either space or service hot water by using the solar heat collection and storage system alone.

Electric resistance heaters have the lowest first cost, but often have high operating costs. Water-to-air heat pumps, which use sun-heated water from the storage tank as the evaporator energy source, are an alternative auxiliary heat source. The heat pump's COP is 10 to 14 Btu of heat for each watt-hour of energy supplied to the
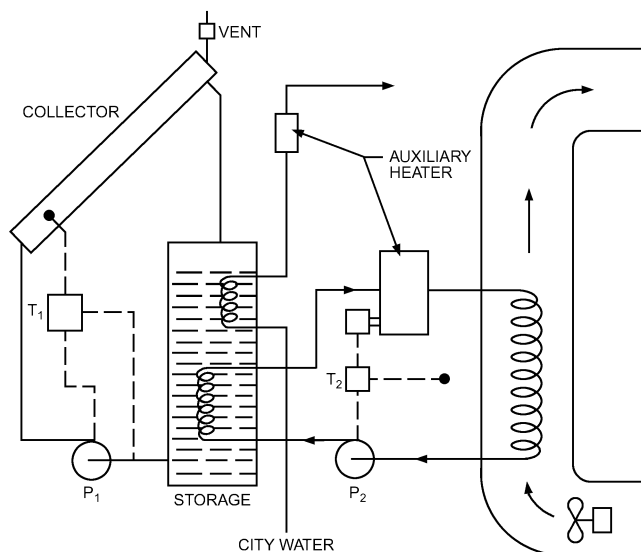
compressor. When summer cooling as well as winter heating are needed, the heat pump becomes a logical solution, particularly in large systems where a cooling tower is used to dissipate the heat withdrawn from the system.

The system shown in Figure 25 may be retrofitted into a warm-air furnace. In such systems, the primary heater is deleted from the space heating circuit, and the coil is located in the return duct of the existing furnace. Full backup is thus obtained, and the auxiliary heater provides only the heat not available at the storage temperature.

COOLING BY SOLAR ENERGY

Swartman et al. (1974) emphasize various absorption systems. Newton (in Jordan and Liu 1977) discusses commercially available water vapor/lithium bromide absorption refrigeration systems. Standard absorption chillers are generally designed to give rated capacity for activating fluid temperatures well above 200°F at full load and design condenser water temperature. Few flat-plate collectors can operate efficiently in this range; therefore, a lower hot-fluid temperature is used when solar energy provides the heat. Both condenser water temperature and percentage of design load are determinants of the optimum energizing temperature, which can be quite low, sometimes below 120°F. Proper control can raise the COP at these part-load conditions.

Many large commercial or institutional cooling installations must operate year-round, and Newton (in Jordon and Liu 1977) showed that the low-temperature cooling water available in winter enables the LiBr/H$_2$O to function well with a hot-fluid inlet temperature below 190°F. Residential chillers in sizes as low as 1.5 tons, with an inlet temperature in the range of 175°F, have been developed.

Solar Cooling with Absorption Refrigeration

When solar energy is used for cooling as well as for heating, the absorption system shown in Figure 26, or one of its many modifications, may be used. The collector and storage must operate at a temperature approaching 200°F on hot summer days when the water from the cooling tower exceeds 80°F, but considerably lower operating water temperatures may be used when cooler water is available from the tower. The controls for collection, cooling, and distribution are generally separated, with the circulating pump P_1 operating in response to the collector thermostat T_1, which is located in the air-conditioned space. When T_2 calls for heating, valves V_1 and V_2 direct the water flow from the storage tank through the unactivated auxiliary heater to the fan coil in the air distribution system. The fan F_1 in this unit may respond to the thermostat also, or it may have its own control circuit so that it can bring in outdoor air when a suitable temperature condition is present.

When thermostat T_2 calls for cooling, the valves direct hot water into the absorption unit's generator, and pumps P_3 and P_4 are activated to pump cooling tower water through the absorber and condenser circuits and chilled water through the cooling coil in the air distribution system. A relatively large hot-water storage tank allows the unit to operate when no sunshine is available. A chilled-water storage tank (not shown) may be added so that the absorption unit can operate during the day whenever water is available at a sufficiently high temperature to make the unit function properly. The COP of a typical lithium bromide/water absorption unit may be as high as 0.75 under favorable conditions, but frequent on/off cycling of the unit to meet a high variable cooling load may cause significant loss in performance because the unit must be heated to operating temperature after each shutdown. Modulating systems are analyzed differently than on/off systems.

Water-cooled condensers are required with the absorption cycles, because the lithium bromide/water cycle operates with a relatively delicate balance among the temperatures of the three fluid

Fig. 25   Solar Collection, Storage, and Distribution System for Domestic Hot Water and Space Heating

circuits (cooling tower water, chilled water, and activating water). The steam-operated absorption systems, from which solar cooling systems are derived, customarily operate at energizing temperatures of 230 to 240°F, but these are above the capability of most flat-plate collectors. The solar cooling units are designed to operate at considerably lower temperature, but unit ratings are also lowered.

Smaller domestic units may operate with natural circulation, or **percolation**, which carries the lithium bromide/water solution from the generator (to which the activating heat is supplied) to the separator and condenser; there, the reconcentrated LiBr is returned to the absorber while the water vapor goes to the condenser before being returned to the evaporator where cooling takes place. Larger units use a centrifugal pump to transfer the fluid.

SIZING SOLAR HEATING AND COOLING SYSTEMS—ENERGY REQUIREMENTS

Methods used to determine solar heating and/or cooling energy requirements for both active and passive/hybrid systems are described by Feldman and Merriam (1979) and Hunn et al. (1987). Descriptions of public- and private-domain methods are included. The following simulation techniques are suitable for active heating and cooling systems analysis, and for passive/hybrid heating, cooling, and lighting analysis.

Performance Evaluation Methods

The performance of any solar energy system is directly related to the (1) heating load, (2) amount of solar radiation available, and (3) solar energy system characteristics. Various calculation methods use different procedures and data when considering the available solar radiation. Some simplified methods consider only average annual incident solar radiation; complex methods may use hourly data.

Solar energy system characteristics, as well as individual component characteristics, are required to evaluate performance. The degree of complexity with which these systems and components are described varies from system to system.

The cost effectiveness of a solar domestic and service hot-water heating system depends on the initial cost and energy cost savings. A major task is to determine how much energy is saved. The **annual solar fraction** (the annual solar contribution to the water-heating load divided by the total water-heating load) can be used to estimate

Fig. 26   Space Heating and Cooling System Using Lithium Bromide-Water Absorption Chiller

these savings. It is expressed as a decimal or percentage and generally ranges from 0.3 to 0.8 (30 to 80%), although more extreme values are possible.

Simplified Analysis Methods

A very simplified way to initially estimate the size of a solar heating system is to divide the average daily load by the daily output of a particular collector based on its SRCC rating for the application and solar conditions. This requires knowledge of the average daily incident solar radiation for the site and the type of collector best suited to the application.

Simplified analysis methods have the advantages of computational speed, low cost, rapid turnaround (especially important during iterative design phases), and ease of use by persons with little technical experience. Disadvantages include limited flexibility for design optimization, lack of control over assumptions, and a limited selection of systems that can be analyzed. Thus, if the application, configuration, or load characteristics under consideration are significantly nonstandard, a detailed computer simulation may be required to achieve accurate results. This section describes the *f*-Chart method for active solar heating and the solar load ratio method for passive solar heating (Dickinson and Cheremisinoff 1980; Klein and Beckman 1979; Lunde 1980).

Water-Heating Load

The amount of hot water required must be estimated accurately because it affects component selection. Oversized storage may result in low-temperature water that requires auxiliary heating to reach the desired supply temperature. Undersizing can prevent the collection and use of available solar energy. Chapter 49 gives methods to determine the load.

Active Heating/Cooling

Beckman et al. (1977) developed the *f*-Chart method using an hourly simulation program (Klein et al. 1976) to evaluate space heating and service water heating in many climates and conditions. The results of these analyses correlate the fraction *f* of the heat load met by solar energy. The correlations give the fraction *f* of the monthly heating load (for space heating and hot water) supplied by solar energy as a function of collector characteristics, heating loads, and weather. The standard error of the differences between detailed simulations in 14 locations in the United States and the *f*-Chart predictions was about 2.5%. Correlations also agree within the accuracy of measurements of long-term performance data. Beckman et al. (1977, 1981) and Duffie and Beckman (1980) discuss the method in detail.

The *f*-Chart method requires the following data:

- Monthly average daily radiation on a horizontal surface
- Monthly average ambient temperatures
- Collector thermal performance curve slope and intercept from standard collector tests; that is, $F_R U_L$ and $F_R(\tau\alpha)_n$ (see ASHRAE *Standard* 93 and Chapter 33 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*)
- Monthly space- and water-heating loads

Standard Systems

The *f*-Chart assumes several standard systems and applies only to these liquid configurations. The standard **liquid heater** uses water, an antifreeze solution, or air as the heat transfer fluid in the collector loop and water as the storage medium (Figure 27). Energy is stored in the form of sensible heat in a water tank. A water-to-air heat exchanger transfers heat from the storage tank to the building. A liquid-to-liquid heat exchanger transfers energy from the main storage tank to a domestic hot-water preheat tank, which in turn supplies solar-heated water to a conventional water heater. A conventional furnace or heat pump is used to meet the space heating load when energy in the storage tank is depleted.
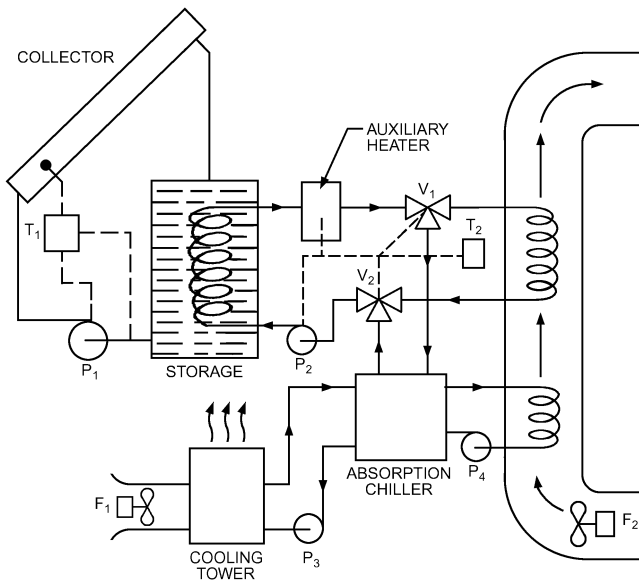
Figure 28 shows the assumed configuration for a **solar air heater** with a pebble-bed storage unit. Energy for domestic hot water is provided by heat exchange from air leaving the collector to a domestic water preheat tank, as in the liquid system. The hot water is further heated, if necessary, by a conventional water heater. During summer operation, a seasonal, manually operated storage bypass damper is used to avoid heat loss from the hot bed into the building.

The standard **solar domestic water heater** collector heats either air or liquid. Collected energy is transferred by a heat exchanger to a domestic water preheat tank that supplies solar-heated water to a conventional water heater. The water is further heated to the desired temperature by conventional fuel if necessary.

f-Chart Method

Computer simulations correlate dimensionless variables and the long-term performance of the systems. The fraction *f* of the monthly space- and water-heating loads supplied by solar energy is empirically related to two dimensionless groups. The first dimensionless group *X* is collector loss; the second *Y* is collector gain:

$$X = \frac{F_R U_L A_c \Delta\theta}{L}\left(\frac{F_r}{F_R}\right)(t_{ref} - \bar{t}_a) \tag{32}$$

$$Y = \frac{F_R(\tau\alpha)_n \overline{H}_T N A_c}{L}\left(\frac{F_r}{F_R}\right)\left[\frac{(\overline{\tau\alpha})}{(\tau\alpha)_n}\right] \tag{33}$$
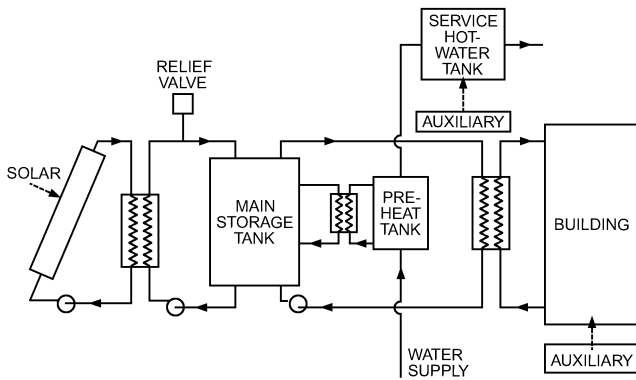
Fig. 27   Liquid-Based Solar Heating System
(Adapted from Beckman et al. 1977)
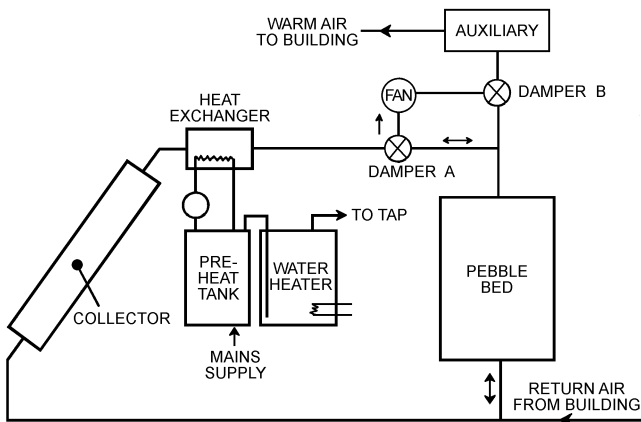
Fig. 28   Solar Air Heating System
(Adapted from Beckman et al. 1977)

where

A_c = area of solar collector, ft^2
F_r = collector heat exchanger efficiency factor
F_R = collector efficiency factor
U_L = collector overall energy loss coefficient, $Btu/h \cdot ft^2 \cdot °F$
$\Delta\theta$ = total number of hours in month
$\bar{t}_a$ = monthly average ambient temperature, °F
L = monthly total heating load for space heating and hot water, Btu
$\overline{H}_T$ = monthly averaged daily radiation incident on collector surface per unit area, $Btu/day \cdot ft^2$
N = number of days in month
$(\overline{\tau\alpha})$ = monthly average transmittance-absorptance product
$(\tau\alpha)_n$ = normal transmittance-absorptance product
t_{ref} = reference temperature, 212°F

$F_R U_L$ and $F_R(\tau\alpha)_n$ are obtained from collector test results. The ratios F_r/F_R and $(\overline{\tau\alpha})/(\tau\alpha)_n$ are calculated using methods given by Beckman et al. (1977). The value of $\bar{t}_a$ is obtained from meteorological records for the month and location desired. $\overline{H}_T$ is calculated from the monthly averaged daily radiation on a horizontal surface by the methods previously discussed in this chapter or in Duffie and Beckman (1992). The monthly load *L* can be determined by any appropriate load estimating method, including analytical techniques or measurements. Values of the collector area A_c are selected for the calculations. Thus, all the terms in these equations can be determined from available information.

Transmittance τ of the transparent collector cover and the absorptance α of the collector plate depend on the angle at which solar radiation is incident on the collector surface. Collector tests are usually run with the radiation incident on the collector in a nearly perpendicular direction. Thus, the value of $F_R(\tau\alpha)_n$ determined from these tests ordinarily corresponds to the transmittance and absorptance values for radiation at normal incidence. Depending on collector orientation and time of year, the monthly average values of transmittance and absorptance can be significantly lower. The *f*-Chart method requires knowledge of the ratio of the monthly average to normal incidence transmittance-absorptance.

The *f*-Chart method for liquid systems is similar to that for air systems. The fraction of the monthly total heating load supplied by the solar air heating system is correlated with the dimensionless groups *X* and *Y*, as shown in Figure 29. To determine the fraction of the heating load supplied by solar energy for a month, values of *X* and *Y* are calculated for the collector and heating load in question. The value of *f* is determined at the intersection of *X* and *Y* on the *f*-Chart, or from the following equivalent equations.
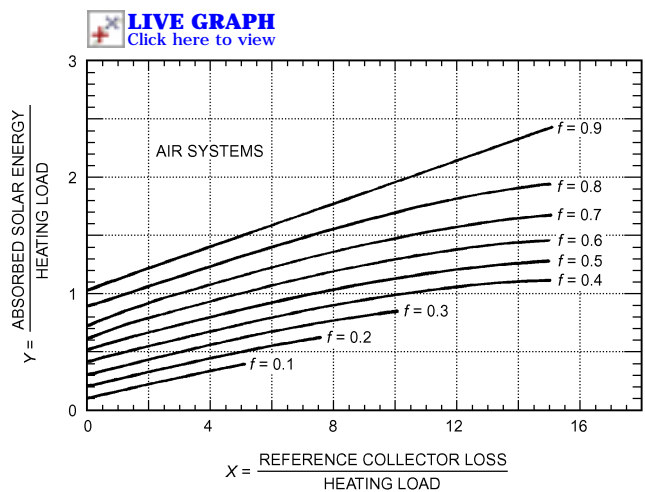
Fig. 29   Chart for Air System
(Adapted from Beckman et al. 1977)

Air system:

$$f = 1.04Y - 0.065X - 0.159Y^2 + 0.00187X^2 - 0.0095Y^3 \qquad (34)$$

Liquid system:

$$f = 1.029Y - 0.065X - 0.245Y^2 + 0.0018X^2 + 0.025Y^3 \qquad (35)$$

This is done for each month of the year. The solar energy contribution for the month is the product of f and the total heating load L for the month. Finally, the fraction F of the annual heating load supplied by solar energy is the sum of the monthly solar energy contributions divided by the annual load:

$$F = \sum fL / \sum L$$

Example 6. Calculating the heating performance of a residence, assume that a solar heating system is to be designed for use in Madison, WI, with two-cover collectors facing south, inclined 58° with respect to the horizontal. The air heating collectors have the characteristics $F_R U_L = 0.50$ Btu/h·ft^2·°F and $F_R(\tau\alpha)_n = 0.49$. The $\bar{t}_a$ is 19.4°F, the total space and water-heating load for January is 34.1×10^6 Btu, and the solar radiation incident on the plane of the collector is 1.16×10^3 Btu/day·ft^2. Determine the fraction of the load supplied by solar energy with a system having a collector area of 538.2 ft^2.

Solution: For air systems, there is no heat exchanger penalty factor and $F_r/F_R = 1$. The value of $(\overline{\tau\alpha})/(\tau\alpha)_n$ is 0.94 for a two-cover collector in January. Therefore, the values of X and Y are

$X = 0.50(1)(212 - 19.4)(31)(24)(538.2)/(34.1 \times 10^6) = 1.13$

$Y = (0.49)(1)(0.94)(1.16 \times 10^3)(31)(538.2)/(34.1 \times 10^6) = 0.26$

Then the fraction f of the energy supplied for January is 0.19. The total solar energy supplied by this system in January is

$$fL = (0.19)(34.1 \times 10^6) = 6.4 \times 10^6 \text{ Btu}$$

The annual system performance is obtained by summing the energy quantities for all months. The result is that 37% of the annual load is supplied by solar energy.

The collector heat removal factor F_R that appears in X and Y is a function of the collector fluid flow rate. Because of the higher cost of power for moving fluid through air collectors than through liquid collectors, the capacitance rate used in air heaters is ordinarily much lower than that in liquid heaters. As a result, air heaters generally have a lower F_R. Values of F_R corresponding to the expected airflow in the collector must be used to calculate X and Y.

Increased airflow rate tends to improve collector performance by increasing F_R, but it tends to decrease performance by reducing the degree of thermal stratification in the pebble bed (or water storage tank). The f-Chart for air systems is based on a collector airflow rate of 2 scfm per square foot of collector area. The performance with different collector airflow rates can be estimated by using the appropriate values of F_R in both X and Y. A further modification to the value of X is required to account for the change in degree of stratification in the pebble bed.

Air system performance is less sensitive to storage capacity than that of liquid systems for two reasons: (1) air systems can operate with air delivered directly to the building in which storage is not used, and (2) pebble beds are highly stratified and additional capacity is effectively added to the cold end of the bed, which is seldom heated and cooled to the same extent as the hot end. The f-Chart for air systems is for a nominal storage capacity. Performance of systems with other storage capacities can be determined by modifying the dimensionless group X as described in Beckman et al. (1977).

With modification, f-Charts can be used to estimate performance of solar water heating operating in the range of 120 to 160°F. The main water supply temperature and minimum acceptable hot-water temperature (i.e., the desired delivery temperature) both affect the performance of solar water heating. The dimensionless group X, which is related to collector energy loss, can be redefined to include these effects. If monthly values of X are multiplied by a correction factor, the f-Chart for liquid-based solar space- and water-heating systems can be used to estimate monthly values of f for water heating. Experiments and analysis show that the load profile for a well-designed heater has little effect on long-term performance. Although the f-Chart was originally developed for two-tank systems, it may be applied to single- and double-tank domestic hot-water systems with and without collector tank heat exchangers. Because of their low rates, use caution when modeling thermosiphon and ICS systems with the f-Chart.

For industrial process heating, absorption air conditioning, or other processes for which the delivery temperature is outside the normal f-Chart range, modified f-Charts are applicable (Klein et al. 1976). The concept underlying these charts is that of solar usability, which is the fraction of the total solar energy that is useful in the given process. This fraction depends on the required delivery temperature as well as collector characteristics and solar radiation. The procedure allows the energy delivered to be calculated in a manner similar to that for f-Charts. An example of the application of this method to solar-assisted heat pumps is presented in Svard et al. (1981).

Other Active Collector Methods

The **relative areas method**, based on correlations of the f-Chart method, predicts annual rather than monthly active heating performance (Barley and Winn 1978). An hourly simulation program has been used to develop the **monthly solar-load ratio (SLR) method**, another simplified procedure for residential systems (Dickinson and Cheremisinoff 1980). Based on hour-by-hour simulations, a method was devised to estimate performance based on monthly values of horizontal solar radiation and heating degree-days. This SLR method has also been extended to nonresidential buildings for a range of design water temperatures (Dickinson and Cheremisinoff 1980; Schnurr et al. 1981).

Passive Heating

A widely accepted simplified passive space heating design tool is the solar-load ratio method (ASHRAE 1984; DOE 1980/1982). It can be applied manually, although like the f-Chart, software is also available. The SLR method for passive systems is based on correlating results of multiple hour-by-hour computer simulations, the algorithms of which have been validated against test cell data for the following generic passive heating types: direct gain, thermal storage wall, and attached sunspace. Monthly and annual performance, as expressed by the auxiliary heating requirement, is predicted by this method. The method applies to single-zone, envelope-dominated buildings. A simplified, annual-basis distillation of SLR results, the **load collector ratio (LCR) method**, and several simple-to-use rules have grown out of the SLR method. Several hand-held calculator and microcomputer programs have been written using the method (Nordham 1981).

The SLR method uses a single dimensionless correlating parameter (SLR), which Balcomb et al. (1982) define as a particular ratio of solar energy gains to building heating load:

$$SLR = \frac{\text{Solar energy absorbed}}{\text{Building heating load}} \qquad (36)$$

A correlation period of 1 month is used; thus the quantities in the SLR are calculated for a 1 month period.

The parameter that is correlated to the SLR, the **solar savings fraction (SSF),** is defined as

$$SSF = 1 - \frac{\text{Auxiliary heat}}{\text{Net reference load}} \qquad (37)$$

The SSF measures the energy saving expected from the passive solar building, relative to a reference nonpassive solar building.

In Equation (37), the net reference load is equal to the degree-day load DD of the nonsolar elements of the building:

$$\text{Net reference load} = (NLC)(DD) \qquad (38)$$

where NLC is the net load coefficient, which is a modified *UA* coefficient computed by leaving out the solar elements of the building. The nominal units are Btu/°F·day. The term DD is the temperature departure in degree-days computed for an appropriate base temperature. A building energy analysis based on the SLR correlations begins with a calculation of the monthly SSF values. The monthly auxiliary heating requirement is then calculated by

$$\text{Auxiliary heat} = (NLC)(DD)(1 - SSF) \qquad (39)$$

Annual auxiliary heat is calculated by summing the monthly values.

By definition, SSF is the fraction of the heat load of the nonsolar portions of the building met by the solar element. If the solar elements of the building (south-facing walls and window in the northern hemisphere) were replaced by other elements so that the net annual flow of heat through these elements was zero, the building's annual heat consumption would be the net reference load. The savings achieved by the solar elements would therefore be the net reference load in Equation (38) minus the auxiliary heat in Equation (39), which gives

$$\text{Solar saving} = (NLC)(DD)(SSF) \qquad (40)$$

Although simple, in many situations and climates, Equation (40) is only approximately true because a normal solar-facing wall with a normal complement of opaque walls and windows has a near-zero effect over the entire heating season. In any case, the auxiliary heat estimate is the primary result and does not depend on this assumption.

The hour-by-hour simulations used as the basis for the SLR correlations are done with a detailed model of the building in which all the design parameters are specified. The only parameter that remains a variable is the solar collector area, which can be expressed in terms of the load collector ratio (LCR):

$$LCR = \frac{NLC}{A_p} = \frac{\text{Net load coefficient}}{\text{Projected collector area}} \qquad (41)$$

Performance variations are estimated from the correlations, which allow the user to account directly for thermostat set point, internal heat generation, glazing orientation, and configuration, shading, and other solar radiation modifiers. Major solar system characteristics are accounted for by selecting one of 94 reference designs. Other design parameters, such as thermal storage thickness and conductivity, and the spacing between glazings, are included in a series of sensitivity calculations obtained using hour-by-hour simulations. The results are generally presented in graphic form so that the designer can see the effect of changing a particular parameter.

Solar radiation correlations for the collector area have been determined using hour-by-hour simulation and typical meteorological year (TMY) weather data. These correlations are expressed as ratios of incident-to-horizontal radiation, transmitted-to-incident radiation, and absorbed-to-transmitted radiation as a function of the latitude minus mid-month solar declination and the atmospheric clearness index K_T.

The performance predictions of the SLR method have been compared to predictions made by the detailed hour-by-hour simulations for a variety of climates in the United States. The standard error in the prediction of the annual SSF, compared to the hour-by-hour simulation, is typically 2 to 4%.

The annual solar savings fraction calculation involves summing the results of 12 monthly calculations. For a particular city, the resulting SSF depends only on the LCR of Equation (41), the type of system, and the temperature base used in calculating the temperature departure. Thus, tables that relate SSF to LCR for various systems and for various degree-day base temperatures may be generated for a particular city. Such tables are easier for hand analysis than are the SLR correlations.

Annual SSF versus LCR tables have been developed for 209 locations in the United States and 14 cities in southern Canada for 94 reference designs and 12 base temperatures (ASHRAE 1984).

Example 7. [Abstracted from the detailed version in Balcomb et al. (1982).] Consider a small office building located in Denver, Colorado, with 3000 ft² of usable space and a sunspace entry foyer that faces due south; the projected collector area A_p is 420 ft². A sketch and preliminary plan are shown in Figure 30. Distribution of solar heat to the offices is primarily by convection through the doorways from the sunspace. The principal thermal mass is in the common wall that separates the sunspace from the offices and in the sunspace floor. Even though lighting and cooling are likely to have the greatest energy costs for this building, heating is a significant energy item and should be addressed by a design that integrates passive solar heating, cooling, and lighting.

Solution: Table 5 shows calculations of the net load coefficient. Then,

$$NLC = 24 \times 525 = 12,600 \text{ Btu/°F·day}$$

and the total load coefficient includes the solar aperture

$$TLC = 24 \times 676 = 16,224 \text{ Btu/°F·day}$$

From Equation (43), the load collector ratio is

$$LCR = 12,600/420 = 30 \text{ Btu/ft}^2\cdot\text{°F·day}$$

If the daily internal heat is 130,000 Btu/day, and the average thermostat setting is 68°F, then

$$T_{base} = 68 - 130,000/16,224 = 60\text{°F}$$

(Note that solar gains to the space are not included in the internal gain term as they customarily are for nonsolar buildings.)

In this example, the solar system is type SSD1, defined in ASHRAE (1984) and Balcomb et al. (1982). It is a semiclosed sunspace with a 12 in. masonry common wall between it and the heated space (offices). The aperture is double-glazed, with a 50° tilt and no night insulation. To achieve a projected area of 420 ft², a sloped glazed area of 420/sin 50° = 548 ft² is required.

The SLR correlation for solar system type SSD1 is shown in Figure 31. Values of the absorbed solar energy *S* and heating degree-days DD to base temperature 60°F are determined monthly. For *S*, the solar
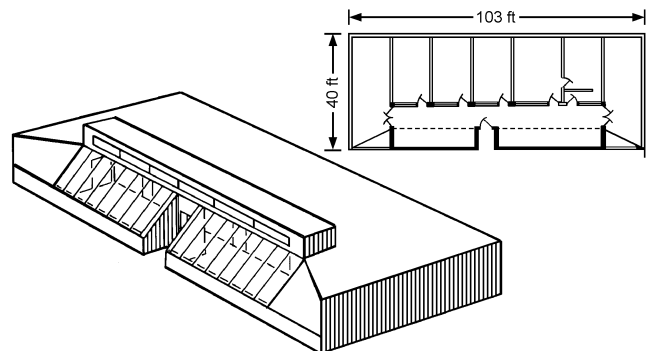
Fig. 30   Commercial Building in Example 7
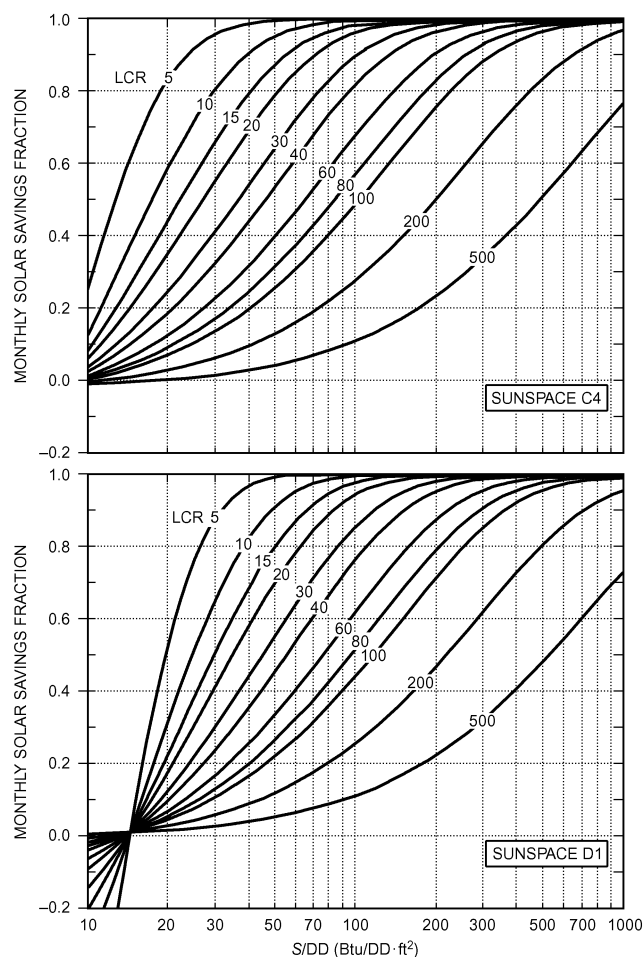
Fig. 31 Monthly SSF Versus Monthly *S*/DD for
Various LCR Values

Table 5 Calculations for Example 7

	Area *A*, ft^2	U-Factor, Btu/h·ft^2·°F	UA, Btu/h·°F
Opaque wall	2000	0.04	80
Ceiling	3000	0.03	90
Floor (over crawl space)	3000	0.04	120
Windows (E, W, N)	100	0.55	55
		Subtotal	345
Infiltration			180
		Subtotal	525
Sunspace (treated as unheated space)			151
		Total	676

ASHRAE procedures are approximated with V = volume, ft^3; c = heat capacity of Denver air, Btu/ft^3·°F; ACH = air changes/h; equivalent UA for infiltration = VcACH. In this case, V = 24,000 ft^3, c = 0.015 Btu/ft^3·°F, and ACH = 0.5.

radiation correlation presented in ASHRAE (1984) for tabulated Denver, CO, weather data is used. For January, the horizontal surface incident radiation is 840 Btu/ft^2·day. The 60°F base degree-days are 933. Using the tabulated incident-to-absorbed coefficients found in ASHRAE (1984), S = 43,681 Btu/ft^2. Thus S/DD = 46.8 Btu/ft^2·°F·day. From Figure 31, at an LCR = 30 Btu/ft^2·°F·day, the SSF = 0.51. Therefore, for January,

$$\text{Net reference load} = (933)(12,600) = 11.76 \times 10^6 \text{ Btu}$$

$$\text{Solar savings} = (11.76 \times 10^6)(0.51) = 6.00 \times 10^6 \text{ Btu}$$

$$\text{Auxiliary heat} = (11.76 \times 10^6) - (6.00 \times 10^6) = 5.76 \times 10^6 \text{ Btu}$$

Repeating this calculation for each month and adding the results for the year yields an annual auxiliary heat of 19.94 × 10^6 Btu.

Other Passive Heating Methods

The concept of usability has been applied to passive buildings. In this approach, the energy requirements of zero- and infinite-capacity buildings are calculated. The amount of solar energy that enters the building and exceeds the instantaneous load of the zero-capacity building is then calculated. This excess energy must be dumped in the zero-capacity building, but it can be stored to offset heating loads in a finite-capacity building. Methods are provided to interpolate between the zero- and infinite-capacity limits for finite-capacity buildings. Equations and graphs for direct gain and collector-storage wall systems are given in Monsen et al. (1981, 1982).

INSTALLATION GUIDELINES

Most solar components are the same as those in HVAC and hot-water systems (pumps, piping, valves, and controls), and their installation is not much different from a conventional installation. Solar collectors are the most unfamiliar component in a solar heater. They are located outdoors, which requires penetration of the building envelope. They also require a structural element to support them at the proper tilt and orientation toward the sun.

The site must taken into account. Collectors should be (1) located so that shading is minimized and (2) installed so that they are attractive both on and off site. They should also be located to minimize vandalism and to avoid a safety hazard.

Collectors should be placed near the storage tank to reduce piping cost and heat loss. The collector and piping must be installed so that they can be drained without trapping fluid in the system.

For best annual performance, collectors should be installed at a tilt angle above the horizontal that is appropriate for the local latitude. In the northern hemisphere they should be oriented toward true south, not magnetic south. Small variations in tilt (±10°) and orientation (±20°) do not reduce performance significantly.

Collector Mounting

Solar thermal collectors are usually mounted on the ground or on flat or pitched roofs. A roof location necessitates penetration of the building envelope by mounting hardware, piping, and control wiring. Ground or flat-roof-mounted collectors are generally rack mounted.

Pitched-roof mounting can be done several ways. Collectors can be mounted on structural **standoffs**, which support them at an angle other than that of the roof to optimize solar tilt. In another pitched-roof-mounting technique known as **direct mounting**, collectors are placed on a waterproof membrane on top of the roof sheeting. The finished roof surface together with the necessary collector structural attachments and flashing are then built up around the collector. A weatherproof seal between the collector and the roof must be maintained to prevent leakage, mildew, and rotting.

Integral mounting can be done for new pitched-roof or curtain-wall construction. The collector is attached to and supported by the structural framing members. The top of the collector then serves as the finished roof surface. Weathertightness is crucial to avoid damage and mildew. This building-integrated approach is often incorporated in green building design and generally is used for photovoltaic modules, rather than thermal collectors.

Collectors should support snow loads that occur on the roof area they cover. The collector tilt usually expedites snow sliding with only a small loss in efficiency. The roof structure should be free of objects that could impede snow sliding, and the collectors should be raised high enough to prevent snow buildup over them.

The mounting structure should be built to withstand winds of at least 100 mph, which impose a wind load of 40 lb/ft^2 on a vertical surface or an average of 25 lb/ft^2 on a tilted roof (HUD 1977). Wind load requirements may be higher, depending on local building codes, especially in coastal areas exposed to hurricanes. Flat-plate

collectors mounted flush with the roof surface should be constructed to withstand the same wind loads. See Chapter 54 for additional information.

The collector array becomes more vulnerable to wind gusts as the angle of the mount increases. This wind load, in addition to the equivalent roof area wind loads, should be determined according to accepted engineering procedures (ASCE *Standards* 7, 8, and 9).

Expansion and contraction of system components, material compatibility, and use of dissimilar metals must be considered. Collector arrays and mounting hardware (bolts, screws, washers, and angles) must be well protected from corrosion. Steel mounting hardware in contact with aluminum and copper piping in contact with aluminum hardware are both examples of metal combinations that have a high potential for corrosion. Dissimilar metals can be separated by washers made of fluorocarbon polymer, phenolic, or neoprene rubber.

Freeze Protection

Freeze protection is extremely important and is often the determining factor when selecting a system in the United States. Freezing can occur at ambient temperatures as high as 42°F because of radiation to the night sky. Manual freeze protection should not be used for commercial installations.

One simple way of protecting against freezing is to drain fluid from the collector array and interior piping when potential freezing conditions exist. Drainage may be automatic, as in draindown and drainback systems, or manual, as in direct thermosiphon systems. Automatic systems should be capable of fail-safe drainage operation, even in the event of pump failure or power outage. In some cases water may be designed to drain back through the pump, so the design must allow refilling without causing cavitation.

In areas where freezing is infrequent, recirculating water from storage to the collector array can be used as freeze protection. Freeze protection can also be provided by using fluids that resist freezing. Fluids such as water/glycol solutions, silicone oils, and hydrocarbon oils are circulated by pumps through the collector array and double wall heat exchanger. Draining the collector fluid is not required, because these fluids have freezing points well below the coldest anticipated outdoor temperature.

In mild climates where recirculation freeze protection is used, a second level of freeze protection should be provided by flushing the collector with cold supply water when the collector approaches near-freezing temperatures. This can be accomplished with a temperature-controlled valve that will automatically open a small port at a near-freezing temperature of about 40°F and then close at a slightly higher temperature.

Overheat Protection

During periods of high insolation and low hot-water demand, overheating can occur in the collectors or storage tanks. Protection against overheating must be considered for all portions of the solar hot-water system. Liquid expansion or excessive pressure can burst piping or storage tanks. Steam or other gases within a system can restrict liquid flow, making the system inoperable.

The most common methods of overheat protection stop circulation in the collection loop until the storage temperature decreases, discharge the overheated water and replace it with cold makeup water, or use a heat exchanger as a means of heat rejection. Some freeze protection methods can also provide overheat protection.

For nonfreezing fluids such as glycol antifreezes, overheat protection is needed to limit fluid degradation at high temperatures during collector stagnation.

Safety

Safety precautions required for installing, operating, and servicing a solar domestic hot-water heater are essentially the same as those for a conventional domestic hot-water heater. One major exception is that some solar systems use nonpotable heat transfer fluids. Local codes may require a double-wall heat exchanger for potable water installations.

Pressure relief must be provided in all parts of the collector array that can be isolated by valves. The outlet of these relief valves should be piped to a container or drain, and not where people could be affected.

Start-Up Commissioning Procedure

After completing the installation, certain tests must be performed before charging or filling the system. The system must be checked for leakage, and pumps, fans, valves, and sensors must be checked to see that they function. Testing procedures vary with system type.

Closed-loop systems should be hydrostatically tested. The system is filled and pressurized to 1.5 times the operating pressure for one hour and inspected for leaks and any appreciable pressure drop.

Draindown systems should be tested to be sure that all water drains from the collectors and piping located outdoors. All lines should be checked for proper pitch so that gravity drains them completely. All valves should be verified to be in working order.

Drainback systems should be tested to ensure that collector fluid drains back to the reservoir tank when circulation stops and that the system refills properly.

Air systems should be tested for leaks before insulation is applied by starting the fans and checking the ductwork for leaks.

Pumps and sensors should be inspected to verify that they are in proper working order. Proper cycling of the pumps can be checked by a running time meter. A sensor that is suspected of being faulty can be dipped alternately in hot and cold water to see if the pump starts or stops.

After system testing and before filling or charging it with heat transfer fluid, the system should be flushed to remove debris.

Maintenance

All systems should be checked at least once a year in addition to any periodic maintenance that may be required for specific components. A log of all maintenance performed should be kept, along with an owner's manual that describes system operational characteristics and maintenance requirements.

The collectors' outer glazing should be hosed down periodically. Leaves, seeds, dirt, and other debris should be carefully swept from the collectors. Care should be taken not to damage plastic covers.

Without opening a sealed collector panel, the absorber plate should be checked for surface coating damage caused by peeling, crazing, or scratching. Also, the collector tubing should be inspected to ensure that it contacts the absorber. If the tubing is loose, the manufacturer should be consulted for repair instructions.

Heat transfer fluids should be tested and replaced at intervals suggested by the manufacturer. Also, the solar energy storage tank should be drained about every six months to remove sediment.

The system designer and installer should provide the building owner with an operating manual that describes maintenance procedures and operating modes in sufficient detail to support ongoing performance.

Performance Monitoring/Minimum Instrumentation

Temperature sensors and temperature differential controllers are required to operate most solar systems. However, additional instruments should be installed for monitoring, checking, and troubleshooting.

Thermometers should be located on the collector supply and return lines so that the temperature difference in the lines can be determined visually.

A pressure gage should be inserted on the discharge side of the pump. The gage can be used to monitor the pressure that the

pump must work against and to indicate if the flow passages are blocked.

Running time meters on pumps and fans may be installed to determine if the system is cycling properly.

DESIGN, INSTALLATION, AND OPERATION CHECKLIST

The following checklist is for designers of solar heating and cooling systems. Specific values have not been included because these vary for each application. The designer must decide whether design figures are within acceptable limits for any particular project [see DOE (1978b) for further information]. The review order listed does not reflect their precedence or importance during design.

Collectors

- Check flow rate for compliance with manufacturer's recommendation.
- Check that collector area matches the application and claimed solar fraction of the load.
- Review collector instantaneous efficiency curve and check match between collector and system requirements.
- Relate collector construction to end use; two cover plates are not required for low-temperature collection in warm climates and may, in fact, be detrimental. Two cover plates are more efficient when the temperature difference between the absorber plate and outdoor air is high, such as in severe winter climates or when collecting at high temperatures for cooling. Radiation loss only becomes significant at relatively high absorber plate temperatures. Selective surfaces should be used in these cases. Flat black surfaces are acceptable and sometimes more desirable for low collection temperatures.
- Check match between collector tilt angle, latitude, and collector end use.
- Check collector azimuth.
- Check collector location for potential shading and exposure to vandalism or accidental damage.
- Review provisions for high stagnation temperature. If not used, are liquid collectors drained or left filled in summer?
- Check for snow hang-up and ice formation. Will casing vents become blocked?
- Review precautions, if any, against outgassing.
- Check access for cleaning covers.
- Check mounting for stability in high winds.
- Check for architectural integration. Do collectors on roof present rainwater drainage or condensation problems? Do roof penetrations present potential leak problems?
- Check collector construction for structural integrity and durability. Will materials deteriorate under operating conditions? Will any pieces fall off?
- Are liquid collector passages organized in such a way as to allow natural fill and drain? Does mounting configuration affect this?
- Does air collector duct connection promote balanced airflow and even heat transfer? Are connections potentially leaky?

Heat Transfer Fluid

- Check that flow rate through the collector array matches system parameters.
- If antifreeze is used, check that flow rate has been modified to allow for the viscosity and specific heat.
- Review properties of proposed antifreeze. Some fluids are highly flammable. Check toxicity, vapor pressure, flash point, and boiling and freezing temperatures at atmospheric pressure.
- Check means of makeup into antifreeze system. An automatic water makeup system can result in freezing.
- Check that provisions are made for draining and filling the system (air vents at high points, drains at low points, pipes correctly graded in-between, drainback vented to storage or expansion tank).
- If system uses drainback freeze protection, check that
  - Provision is made for drainback volume and back venting
  - Pipes are graded for drainback
  - Solar primary pump is sized for lift head
  - Pump is self-priming if tank is below pump
- Check that collector pressure drop for drainback is slightly higher than static pressure between supply and return headers.
- Optimum pipe arrangement is reverse-return with collectors in parallel. Series collectors reduce flow rate and increase head. A combination of parallel/series can sometimes be beneficial, but check that equipment has been sized and selected properly.
- Cross-connections under different operating modes sometimes result in pumps operating in opposition or tandem, causing severe hydraulic problems.
- If heat exchangers are used, check that approach temperature differential has been recognized in the calculations.
- Check that adequate provisions are made for water expansion and contraction. Use specific volume/temperature tables for calculation. Each unique circuit must have its own provision for expansion and contraction.
- Three-port valves tend to leak through the closed port. This, together with reversed flows in some modes, can cause potential hydraulic problems. As a general rule, simple circuits and controls are better.

Airflow

- Check that flow rate through the collector array matches system design values.
- Check temperature rise across collectors using air mass flow and specific heat.
- Check that duct velocities are within design limits.
- Check that cold air or water cannot flow from collectors by gravity under "no-sun" conditions.
- Verify duct material and construction methods. Ductwork must be sealed to reduce loss.
- Check duct configuration for balanced flow through collector array.
- Check number of collectors in series. More than two collectors in series can reduce collection efficiency.

Thermal Storage

- Check that thermal storage capacity matches values of collector area, collection temperature, use temperature, and load.
- Verify that thermal inertia does not impede effective operation.
- Check provisions for promoting temperature stratification during both collection and use.
- Check that pipe and duct connections to storage are compatible with the control, ensuring that only the coolest air goes to the collectors and connections.
- If liquid storage is used for high-temperature (above 200°F) applications, check that tank material and construction can withstand the temperature and pressure.
- Check that storage location does not promote unwanted heat loss or gain and that adequate insulation is provided.
- Verify that liquid storage tanks are treated to resist corrosion. This is particularly important in tanks that are partially filled.
- Check that provision is made to protect liquid tanks from exposure to either an overpressure or vacuum.

Uses

Domestic Hot Water

- Characteristics of domestic hot-water loads include short periods of high draw interspersed with long dormant periods. Check that domestic hot-water storage matches solar heat input.

- Check that provisions have been made to prevent reverse heating of the solar thermal storage by the domestic hot-water back-up heater.
- Check that the design allows cold makeup water preheating on days of low solar input.
- Verify that the antiscald valve limits domestic hot-water supply to a safe temperature during periods of high solar input.
- Depending on total dissolved solids, city water heated above 150°F may precipitate a calcium carbonate scale. If collectors are used to heat water directly, check provisions for preventing scale formation in absorber plate waterways.
- Check whether the heater is required to have a double-wall heat exchanger and that it conforms to appropriate codes if the collector uses nonpotable fluids.

Heating

- Warm-air heating systems have the potential of using solar energy directly at moderate temperatures. Check that air volume is sufficient to meet the heating load at low supply temperatures and that the limit thermostat has been reset.
- At times of low solar input, solar heat can still be used to meet part of the load by preheating return air. Check location of solar heating coil in system.
- Baseboard heaters require relatively high supply temperatures for satisfactory operation. Their output varies as the 1.5 power of the log mean temperature difference and falls off drastically at low temperatures. If solar is combined with baseboard heating, check that supply temperature is compatible with heating load.
- Heat exchangers imply an approach temperature difference that must be added to the system operating temperature to derive the minimum collection temperature. Verify calculations.
- Water-to-air heat pumps rely on a constant solar water heat source for operation. When the heat source is depleted, the back-up system must be used. Check that storage is adequate.

Cooling

- Solar-activated absorption cooling with fossil fuel back-up is currently the only commercially available active cooling. Be assured of all design criteria and a large amount of solar participation. Verify calculations.
- Storing both hot and chilled water may make better use of available storage capacity.

Controls

- Check that control design matches desired modes of operation.
- Verify that collector loop controls recognize solar input, collector temperature, and storage temperature.
- Verify that controls allow both the collector and usage loops to operate independently.
- Check that control sequences are reversible and always revert to the most economical mode.
- Check that controls are as simple as possible within the system requirements. Complex controls increase the frequency and possibility of breakdowns.
- Check that all controls are fail-safe.

Performance

- Check building heating, cooling, and domestic hot-water loads as applicable. Verify that building thermal characteristics are acceptable.
- Check solar energy collected on a monthly basis. Compare with loads and verify solar participation.

PHOTOVOLTAIC APPLICATIONS

Photovoltaic (PV) solar collectors, called PV modules, convert light directly into electricity. Chapter 33 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment* discusses the fundamentals of

their operation. Photovoltaics are used to power remotely located communications equipment, remote monitoring, lighting, water pumping, battery charging, and cathodic protection, and for utility interactive power generation. The first step for any PV application is to analyze electric loads and then minimize them wherever possible. PV array size can be reduced substantially by using high-efficiency HVAC, appliances, motors, and other power-consuming devices. Using this strategy is almost always more cost-effective than adding more PV modules.

Communications. Photovoltaics can provide reliable power with little maintenance for communications systems, especially those in remote areas (away from the power grid) with extreme weather conditions such as high winds, heavy snows, and ice. Examples include communication relay towers, travelers' information transmitters, cellular telephones, mobile radio systems, emergency call boxes, and military test facilities. These systems range in size from a few watts for call boxes to several kilowatts for microwave repeater stations. For larger systems at remote sites, an engine generator is often combined with the photovoltaic-battery system. These hybrid systems with two or more generators can achieve nearly 100% availability.

Remote Site Electrification. Photovoltaics are used to provide power to rural residences, visitor centers in parks, vacation cabins, island and villages, remote research facilities, and military test areas. The varied loads include lighting, small appliances, water pumps (including circulators on solar water-heating systems), and communications equipment. The load demand varies from a few watts to tens of kilowatts. Deep-cycle battery back-up is most often used in this application for nighttime power, and is typically sized to meet the load for two to three days without PV input. Hybrid systems are also common, using wind or small hydro generation equipment.

Remote Monitoring. Photovoltaics provide power at remote sites to sensors, data loggers, and associated transmitters for meteorological monitoring, structural condition measurement, seismic recording, irrigation control, highway/traffic monitoring, security monitoring, and scientific research. Most of these applications require less than 200 W, and many can be powered by a single photovoltaic module. Vandalism may be a problem in some areas, so non-glass-covered modules are sometimes used. Mounting the modules on a tall pole or in an unobtrusive manner may also help avoid damage or theft. The batteries are often located in the same weather-resistant enclosure as the data acquisition/monitoring equipment. This enclosure is sometimes camouflaged or buried for protection. Some data loggers come with their own battery and charge regulator.

Signs and Signals. The most popular application for photovoltaics is warning signs. Typical devices include navigational beacons, audible signals such as sirens, highway warning signs, railroad signals, and aircraft warning beacons. Because these signals are critical to public safety, they must be operative at all times, and thus the reliability of the photovoltaic system is extremely important. High reliability can be achieved by using large-capacity batteries. Many of these systems operate in harsh environments. For maritime applications, special modules are used that are resistant to corrosion from salt water.

Water Pumping and Control. Photovoltaics are typically used for intermediate-sized water pumping applications (those larger than hand pumps and smaller than large engine-powered pumps). The range of sizes for photovoltaic-powered pumps is a few hundred watts to a few kilowatts. Applications include domestic use, water for campgrounds, irrigation, village water supplies, and livestock watering. Photovoltaics for livestock watering can be more economical than maintaining a distribution line to a remote pump on a ranch. Most pumping systems do not use batteries but store the water in holding tanks. For this application, the photovoltaic modules may be mounted on tracking frames that maximize energy production by tracking the sun each day.

Rest Room Facilities. Highway rest stops, public beach facilities, outdoor recreation parks, and public campgrounds may have photovoltaics to operate air circulation and ventilation fans, interior and exterior lights, and auxiliary water pumps for sinks and showers. For most of these applications, the initial cost for photovoltaic power is the least expensive option.

Charging Auto, Boat, and RV Batteries. Batteries self-discharge over time if they are not used. This is a problem for organizations that maintain a fleet of vehicles such as fire-fighting or snow removal equipment, some of which are infrequently used. Photovoltaic battery chargers can solve this problem by providing a trickle charging current that keeps the battery at a high state of charge. Often the PV module can be placed inside the windshield and plugged into the vehicle's power socket, thus using existing wiring and protection circuits and providing a quick disconnect for the module. Modules are installed on the roof or engine hood of larger vehicles. Another successful application is using PV modules to charge the batteries in electric vehicles.

Grid-Connected Systems. Grid-connected or utility-interactive PV systems use an inverter that converts dc output from the PV array to ac current. It is designed to operate in conjunction with the electric utility mains, synchronizing the ac output (phase, frequency, and voltage) with the utility. The PV output is directly connected to the inverter, and the ac output from the inverter is connected to the ac load circuit. Excess power generated during the day is fed back to the utility grid, and grid power is used at night. **Net metering** uses a single utility meter; when energy is fed back to the utility grid, the meter runs backwards.

SYMBOLS

a = constant for specified month at specified location
A = apparent extraterrestrial irradiation at $m = 0$
A_{abs}, A_{ap} = areas of absorber surface and of aperture that admit or receive radiation, ft^2
A_{ap} = aperture area
A_c = area of solar collector, ft^2
A_g = gross collector area
A_p = projected collector area
AST = apparent solar time
b = constant for specified month at specified location
B = atmospheric extinction coefficient
C = parameter depending on dust and moisture content of atmosphere
c_p = specific heat of fluid, Btu/lb·°F
DD = degree-day load of nonsolar elements
DST = daylight saving time
e_{at} = sky emittance
e_s = surface emittance
f = fraction of monthly space- and water-heating loads supplied by solar energy
F_r = collector heat exchanger efficiency factor
F_R = collector heat removal factor; ratio of heat actually delivered by collector to heat that would be delivered if absorber were at t_{fi}
F_{sg} = angle factor between surface and earth; Equation (17)
F_{ss} = angle factor between surface and sky; Equation (15)
H = hour angle
H_T = monthly averaged daily radiation incident on collector surface per unit area, Btu/day·ft^2
I_{dH} = diffuse radiation falling on horizontal surface under cloudless sky
I_{DN} = direct normal irradiation, Btu/h·ft^2
$I_{d\theta}$ = diffuse component of solar radiation from sky
I_r = reflected shortwave radiation
I_{tH} = total horizon irradiation
$I_{t\theta}$ = total solar irradiation of terrestrial surface or collector, Btu/h·ft^2
K_T = atmospheric clearness index

L = monthly total heating load for space heating and hot water, Btu
LCR = load collector ratio; net load coefficient divided by projected collector area
LST = local standard time
m = air mass; = 1.0/sin β at sea level and 0 outside earth's atmosphere; also fluid flow rate, lb/h
N = year day, with January 1 = 1; also number of days in month
NLC = net load coefficient
q_{Rat} = downward radiation from atmosphere
q_{Rs} = longwave radiation emitted by surface on earth
q_u = useful heat gained by collector per unit of aperture area, Btu/h·ft^2
R_{net} = net radiative cooling rate of horizontal surface
S = total downward radiant heat flux from atmosphere
SSF = solar savings fraction
SLR = solar energy absorbed divided by building heating load
t_a = temperature of atmosphere, or monthly average ambient temperature, °F
t_{abs} = temperature of absorber, °F
T_{base} = base temperature
t_{fe}, t_{fi} = temperatures of fluid leaving and entering collector, respectively, °F
TLC = total load coefficient
t_p = temperature of absorber plate, °F
T_{rad} = absolute temperature of horizontal surface, °R
t_{ref} = reference temperature, 212°F
T_s = absolute temperature of surface, °R
T_{sky} = apparent sky temperature, °R
U_L = upward heat loss coefficient, Btu/h·ft^2·°F
X = reference collector loss divided by heating load
Y = absorbed solar energy divided by heating load

Greek

α = absorptance
β = sun's altitude above horizon
γ = surface-solar azimuth
δ = solar declination
$\Delta\theta$ = total number of hours in month
ϵ = nonspectral emittance of horizontal surface; about 0.9 for most nonmetallic construction materials
η = collector efficiency
θ = solar incident angle
ρ_g = reflectance of foreground
$\rho\Gamma$ = reflectance of concentrator surface times fraction of reflected or refracted radiation that reaches absorber
σ = Stefan-Boltzmann constant, 0.1712×10^{-8} Btu/h·ft^2·°R^4
Σ = tilt angle of surface, measured from horizontal
τ = transmittance
$(\tau\alpha)$ = monthly average transmittance-absorptance product
$(\tau\alpha)_n$ = normal transmittance-absorptance product
$(\tau\alpha)_\theta$ = transmittance τ of cover times absorptance α of plate at prevailing incident angle θ
ϕ = solar azimuth
ψ = surface azimuth

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CHAPTER 34

THERMAL STORAGE

THERMAL storage systems remove heat from or add heat to a storage medium for use at another time. Thermal energy storage for HVAC applications can involve various temperatures associated with heating or cooling. High-temperature storage is typically associated with solar energy or high-temperature heating, and cool storage with air-conditioning, refrigeration, or cryogenic-temperature processes. Energy may be charged, stored, and discharged daily, weekly, annually, or in seasonal or rapid batch process cycles. Currently, most use of thermal storage is cool storage for comfort and process cooling applications as a way to reduce the total utility bill and/or size of cooling equipment, and much of the discussion in this chapter pertains specifically to cool storage. The *Design Guide for Cool Thermal Storage* (Dorgan and Elleson 1993) covers cool storage issues and design parameters in detail.

A properly designed and installed thermal storage system can

- Reduce operating or initial costs
- Reduce size of electric service and cooling or heating equipment
- Increase operating flexibility
- Provide back-up capacity
- Extend the capacity of an existing system

Benefits are discussed further in the Benefits of Thermal Storage section.

Thermal storage may be a particularly attractive approach to meeting heating or cooling loads if one or more of the following conditions apply:

- Loads are of short duration
- Loads occur infrequently
- Loads are cyclical
- Loads are not coincident with energy source availability
- Energy costs are time-dependent (e.g., time-of-use energy rates)
- Charges for peak power demand are high
- Utility rebates, tax credits, or other economic incentives are provided for using load-shifting equipment
- Energy supply is limited, thus limiting or preventing the use of full-size nonstorage systems
- Facility expansion is planned, and the existing heating or cooling equipment is insufficient to meet the new peak load but has spare nonpeak capacity
- Interruption in cooling water cannot be tolerated by a mission-critical operation

Terminology

Charging. Storing cooling capacity by removing heat from a cool storage device, or storing heating capacity by adding heat to a heat storage device.

Chiller priority. Control strategy for partial storage systems that uses the chiller to directly meet as much of the load as possible, normally by operating at full capacity most of the time. Thermal storage is used to supplement chiller operation only when the load exceeds the chiller capacity.

Cool storage. As used in this chapter, storage of cooling capacity in a storage medium at temperatures below the nominal temperature of the space or process.

Demand limiting. A partial storage operating strategy that limits capacity of refrigeration equipment during the on-peak period. Refrigeration equipment capacity may be limited based on its cooling capacity, its electric demand, or the facility demand.

Design load profile. Calculated or measured hour-by-hour cooling loads over a complete cooling cycle that are considered to be the desired total cooling load that must be met by mechanical refrigeration and capacity from a cool thermal storage system.

Design operating profile. Equipment hour-by-hour operation, including mechanical refrigeration equipment, the thermal storage system's charge or discharge rate, and temperatures over the entire cooling system operating period.

Discharging. Using stored cooling capacity by adding thermal energy to a cool storage device or removing thermal energy from a heat storage device.

Encapsulated storage. A latent storage technology that consists of plastic containers of water or other phase-change material that are alternately frozen and melted by the influence of glycol or other secondary coolant medium in which they are immersed.

Full storage. A cool storage sizing strategy that meets the entire cooling load with discharge from the thermal storage system for some period, typically hours when loads are high and electric power is expensive.

Fully charged condition. State of a cool thermal storage system at which, according to design, no more heat is to be removed from the storage device. This state is generally reached when the control system stops the charge cycle as part of its normal control sequence, or when the maximum allowable charging period has elapsed.

Fully discharged condition. State of a cool thermal storage system at which no more usable cooling capacity can be delivered from the storage device.

Heat storage. As used in this chapter, storage of thermal energy at temperatures above the nominal temperature of the space or process.

Ice harvester. Machine that cyclically forms a layer of ice on a smooth cooling surface, using refrigerant inside the heat exchanger, then delivers it to a storage container by heating the surface of the cooling plate, normally by reversing the refrigeration process and delivering hot gases inside the heat exchanger.

Ice-on-coil (ice-on-pipe). Ice storage technology that forms and stores ice on the outside of tubes or pipes submerged in an insulated water tank.

Ice-on-coil, external melt. Ice storage technology in which tubes or pipes (coil) are immersed in water and ice is formed on the outside of the tubes or pipes by circulating colder secondary medium or refrigerant inside the tubing or pipes, and is melted externally by circulating unfrozen water outside the tubes or pipes to the load.

The preparation of this chapter is assigned to TC 6.9, Thermal Storage.

Ice-on-coil, internal melt. Ice storage technology in which tubes or pipes (coil) are immersed in water and ice is formed on the outside of the tubes or pipes by circulating colder secondary medium or refrigerant inside the tubing or pipes, and is melted internally by circulating the same secondary coolant or refrigerant to the load.

Latent energy storage (latent heat storage). A thermal storage technology in which energy is stored within a medium, normally associated with a phase change (usually between solid and liquid states), for use in cooling or heating the secondary liquid being circulated through the system.

Load leveling. A partial storage sizing strategy that minimizes storage equipment size and storage capacity. The system operates with refrigeration equipment running at full capacity for 24 h to meet the normal cooling minimum load profile and, when load is less than the chiller output, excess cooling is stored. When load exceeds chiller capacity, the additional cooling requirement is obtained from the thermal storage.

Load profile. Compilation of instantaneous thermal loads over a period of time, normally 24 h.

Mass storage. Storage of energy, in the form of sensible heat, in building materials, interior equipment, and furnishings.

Maximum usable cooling supply temperature. Maximum fluid supply temperature at which the cooling load can be met. This is generally determined by the requirements of the air-side distribution system or the process.

Maximum usable discharge temperature. Highest temperature at which beneficial cooling can be obtained from the thermal storage device.

Nominal chiller capacity. (1) Chiller capacity at standard Air-Conditioning and Refrigeration Institute (ARI) rating conditions. (2) Chiller capacity at a given operating condition selected for the purpose of quick chiller sizing selections.

Partial storage. A cool storage sizing strategy in which only a portion of the on-peak cooling load is met from thermal storage, with the rest being met by operating the chilling equipment.

Phase-change material (PCM). A substance that undergoes a change of state, normally from solid to liquid or liquid to solid, while absorbing or rejecting thermal energy at a constant temperature.

Pulldown load. Unmet cooling or heating load that accumulates during a period when a cooling or heating system has not operated, or operated in a thermostat setback mode, and which must be met on system start-up before comfort conditions can be achieved. Maximum pulldown load generally occurs on a Monday morning or following an extended shutdown.

Sensible energy storage (sensible heat storage). A heating or cooling thermal storage technology in which all energy stored is in the form of a measurable temperature difference between the hot or chilled water circulating through the system and the storage medium.

Storage cycle. A period in which a complete charge and discharge of a thermal storage device has occurred, beginning and ending at the same state.

Storage inventory. Amount of usable heating or cooling capacity remaining in a thermal storage device.

Storage priority. A control strategy that uses stored cooling to meet as much of the load as possible. Chillers operate only if the load exceeds the storage system's available cooling capacity.

Stratified chilled-water storage. A method of sensible cool thermal energy storage that achieves and maintains an acceptable separation between warm (discharged) and cool (charged) water by forming a thermocline by density differences alone, and not by mechanical separation.

Thermal storage capacity. A value indicating the maximum amount of cooling (or heating) that can be achieved by the stored medium in the thermal storage device.

Discharge capacity. The maximum rate at which cooling can be supplied from a cool storage device.

Nominal storage capacity. A theoretical capacity of the thermal storage device. In many cases, this may be greater than the usable storage capacity. This measure should not be used to compare usable capacities of alternative storage systems.

System capacity. Maximum amount of cooling that can be supplied by the entire cooling system, which may include chillers and thermal storage.

Usable storage capacity. Total amount of beneficial cooling able to be discharged from a thermal storage device. (This may be less than the nominal storage capacity because the distribution header piping may not allow discharging the entire cooling capacity of the thermal storage device.)

Thermal storage device. A container plus all its contents used for storing heating or cooling energy. The heat transfer fluid and accessories, such as heat exchangers, agitators, circulating pumps, flow-switching devices, valves, and baffles that are integral with the container, are considered a part of the thermal storage device.

Thermocline. Thermal layer of water in a chilled-water thermal storage tank, separating warmer water at the top and cooler water at the bottom. The depth of this layer depends on the effectiveness and efficiency of the upper and lower diffusers, which are designed to supply and discharge water with minimal mixing. The typical thermocline is 18 to 24 in., and rises and falls when charging and discharging the storage tank.

Total cooling load. Integrated thermal load that must be met by the cooling plant over a given period of time.

Usable cooling. Amount of energy that can actually be delivered to the system or process to meet cooling requirements. Normally, this is the total value of the energy retrieved by supplying the medium at or below the maximum beneficial cooling temperature.

Classification of Systems

Thermal storage systems can be classified according to the type of thermal storage medium, whether they store primarily sensible or latent energy, or the way the storage medium is used. Cool storage media include chilled water, aqueous or nonaqueous fluids, ice, and phase-change materials. Heat storage media include water, brick, stone, and ceramic materials. These media differ in their heat storage capacities, the temperatures at which energy is stored, and physical requirements of storing energy in the media. Types of cool storage systems include chilled-water storage, chilled-fluid storage, ice harvesting, internal- and external-melt ice-on-coil, encapsulated ice, ice slurry, and phase-change material systems. Types of heat storage systems include brick storage heaters, water storage heaters, and radiant floor heating systems, as well as solar space and water heating and thermally charged water storage tanks.

Storage Media

A wide range of materials can be used as thermal storage media. Materials used for thermal storage should be

- Commonly available
- Low cost
- Environmentally benign
- Nonflammable
- Nonexplosive
- Nontoxic
- Compatible with common HVAC equipment construction materials
- Noncorrosive
- Inert

An ideal thermal storage medium should also have

- Well-documented physical properties
- High density

- High specific heat (for sensible heat storage)
- High heat of fusion (for latent heat storage)
- Good heat transfer characteristics
- Stable properties that do not change over many thermal cycles

Common storage media for sensible energy storage include water, fluid, soil, rock, brick, ceramics, concrete, and various portions of the building structure (or process fluid) being heated or cooled. In HVAC applications, such as air conditioning, space heating, and water heating, water is often the chosen sensible storage medium because it provides many of these desirable characteristics when kept between its freezing and boiling points. For high-temperature energy storage, the storage medium is often rock, brick, or ceramic materials for residential or small commercial applications; oil, oil/rock combinations, or molten salt are often used for large industrial or solar energy power plant applications. Using the building structure itself as passive thermal storage offers advantages under some circumstances (Morris et al. 1994).

Common storage media for latent energy storage include ice, aqueous brine/ice solutions, and other PCMs such as hydrated salts and polymers. Carbon dioxide and paraffin waxes are among the alternative storage media used for latent energy storage at various temperatures. For air-conditioning applications, ice is the most common latent storage medium, because it provides many of the previously listed desirable characteristics.

Basic Thermal Storage Concepts

The fundamental characteristic of thermal storage systems is that they separate the time(s) of generation of heating or cooling from the time(s) of its use. This separation allows thermal storage systems to generate heating or cooling during periods when conditions are most favorable (e.g., the primary energy source is more available or less expensive), which can be independent of the instantaneous thermal load.

A thermal storage system can meet the same total heating or cooling load as a nonstorage system over a given period of time with smaller primary equipment. The total capacity distributed over the period is matched more closely to the total load encountered in the same period. The reduced size and cost of heating or cooling equipment can partially or completely offset the cost of the storage equipment.

Benefits of Thermal Storage

Properly designed, installed, and operated thermal storage systems offer the following benefits for heating and cooling systems.

Energy Cost Savings. The primary benefit of thermal storage is its ability to substantially reduce total operating costs, particularly for systems using electricity as the primary energy source. Thermal storage systems reduce the demand for expensive on-peak electric power, substituting less expensive nighttime power to do the same job. In addition, in many cases thermal energy storage systems actually consume less energy to deliver the same amount of cooling, primarily because of more efficient use of cooling equipment and the constant temperature of the delivered medium.

Reduced Equipment Size. Heating or cooling equipment can be sized to meet the average load rather than the peak load, and the thermal storage system can be sized to pick up the difference in the load.

Capital Cost Savings. The capital savings from downsizing cooling equipment can more than offset the added cost of the storage system (Andrepont 2005). Cool storage integrated with low-temperature air and water distribution systems can also provide an initial cost savings by using smaller chillers, pumps, piping, ducts, and fans. Smaller cooling equipment often allows designers to downsize the transformers and electrical distribution systems that supply power for cooling. This economic benefit can be significant, both in new construction, and in existing facilities where electrical

systems are at or near their full capacity. In some areas, government or utility company incentives are available that can further reduce capital costs.

Energy Savings. Although thermal storage systems are generally designed primarily to shift energy use rather than to conserve energy, they can fill both roles. Cool storage systems allow chillers to operate more at night, when lower condensing temperatures improve equipment efficiency. In addition, thermal storage allows operation of equipment at full load, avoiding inefficient part-load performance. Documented examples include chilled-water storage installations that reduce annual energy consumption on a ton-hour basis for air conditioning by up to 12% (Bahnfleth and Joyce 1994; Fiorino 1994). Heat recovery from chiller condensers can also reduce, or even eliminate, the need for heating equipment and associated energy use by combining cooling thermal storage with heating thermal storage (Goss et al. 1996).

Improved HVAC Operation. Thermal storage allows the thermal load profile to be decoupled from operation of the heating or cooling equipment. This decoupling enables plants to use the optimum combination of primary equipment and storage at any given time, providing increased flexibility, reliability, and efficiency in all seasons.

Back-Up Capacity. Cool storage can substantially reduce the installed cost for back-up or emergency cooling systems by reducing the need for redundant electrical and mechanical equipment. Back-up cooling for critical areas (e.g., computer rooms, hospital operating rooms) can be immediately available from the storage reservoir.

Extending Existing Systems' Capacity. The apparent capacity of existing systems can often be increased by installing cool storage at less cost than adding conventional nonstorage equipment. A chilled-water storage tank adds cooling capacity to an existing system and may avoid the high expense of installing new chillers. With this form of thermal storage, existing chillers can now operate during normally off hours to generate the additional cooling needed. The cooling capability of existing ductwork and piping can also be increased by using cool storage. Supplying chilled water and air at lower temperatures allows existing distribution systems to meet substantially higher loads and reduces pump or fan energy consumption.

Other Benefits. Thermal storage can bring about other beneficial synergies. As already noted, cool storage can be integrated with cold-air distribution. A chilled-water storage tank can serve double duty by providing a fire protection water supply at a much lower cost than installing separate systems (Holness 1992; Hussain and Peters 1992; Meckler 1992). Some cool storage systems can be configured for charging with free cooling. Thermal storage can also be used to recover waste energy from base-loaded steam plants by storing chilled water produced by an absorption chiller for later use on demand.

Design Considerations

Thermal storage systems must be designed to meet the total integrated load as well as the peak hourly load. To properly size a thermal storage system, a designer must calculate an accurate load profile and analyze the thermal performance of the storage equipment over the entire storage cycle. Proper sizing is essential. An undersized thermal storage system is limited in its ability to recover when the load exceeds its capacity. On the other hand, excessive oversizing quickly diminishes the economic benefits of thermal storage. Load calculations and system sizing are discussed in Dorgan and Elleson (1993).

Thermal performance of a thermal storage device varies, depending on the current inventory of stored energy and rate of discharge. Therefore, the total capacity of a given thermal storage device depends on the load profile to which it is subjected. There is no standard method for rating cool storage capacity, so performance

specifications must detail the required thermal performance for each hour of the storage cycle. Thermal performance specifications for cool storage systems are discussed in ASHRAE *Guideline* 4.

A thermal storage system must be controlled according to two separate time schedules. Generation of heating or cooling is controlled on a different schedule from the distribution and utilization.

Thermal storage offers the flexibility to supply heating or cooling from storage, from primary equipment, or from both. With this flexibility comes the need to define how the system will be controlled at any given time. The intended strategy for operation and control must be defined as part of the design procedure, as described in Dorgan and Elleson (1993).

SENSIBLE THERMAL STORAGE TECHNOLOGY

Sensible Energy Storage

Water is well suited for both hot and cold sensible energy storage applications and is the most common sensible storage medium, in part because it has the highest specific heat (1 Btu/lb·°F) of all common materials. ASHRAE *Standard* 94.3 covers procedures for measuring thermal performance of sensible heat storage. Tanks are available in many shapes; however, vertical cylinders are the most common. Tanks can be located above ground, partially buried, or completely buried. They can also be incorporated into the building structure. For economic reasons, they usually operate at atmospheric pressure and may have clear-span dome roofs, column-supported shallow cone roofs, or column-supported flat roofs. Sensible thermal storage vessels must separate the cooler and warmer volumes of storage medium. This section focuses on chilled-water thermal energy storage because it is the most common system type. However, similar techniques apply to hot-water sensible energy storage for heating systems and to aqueous and nonaqueous stratification fluids for cool storage.

Temperature Range and Storage Size

The cooling capacity of a chilled-water storage vessel is proportional to the volume of water stored and the temperature differential (Δt) between the stored cool water and returning warm water. There is a direct relationship between Δt and the size of sensible storage system components. For economical storage, therefore, the cooling loads served by the system should provide as large a Δt as practical. Many chilled-water systems are designed to operate with a Δt between supply and return of 12 to 16°F. Designing for an achievable 20 to 24°F Δt has the potential to decrease storage vessel size by as much as 50% relative to this typical range. The cost of the extra coil surface required to provide this larger Δt can be more than offset by cost reductions of a smaller tank, reduced pipe and insulation size, and significantly reduced pumping energy. Storage is likely to be uneconomical if the Δt is less than about 10°F because the tank must be so large (Caldwell and Bahnfleth 1997). Typical design and operating conditions result in a storage density of approximately 100 gal/ton·h. Maintaining a Δt as large as possible is very important in achieving the intended beneficial performance of the system. The total performance depends on the behavior of connected loads and needs to be addressed as a system issue.

The initial cost of chilled-water cool storage benefits from a dramatic economy of scale; that is, large installations can be much less expensive per amount of discharge than equivalent nonstorage chilled-water plants (Andrepont 1992, 2005; Andrepont and Kohlenberg 2005; Andrepont and Rice 2002).

Techniques for Thermal Separation in Sensible Storage Devices

The following methods have been applied in chilled-water storage. Thermal stratification has become the dominant method

because of its simplicity, reliability, efficiency, and low cost. The other methods are described only for reference.

Thermal Stratification. In stratified cool storage, warmer, less dense return water floats on top of denser chilled water. Cool water from storage is supplied and withdrawn at low velocity, in essentially horizontal flow, so buoyancy forces dominate inertial effects. Pure water is most dense at 39.2°F; therefore, colder water introduced into the bottom of a stratified tank tends to mix to this temperature with warmer water in the tank. However, low-temperature fluids (LTFs), typically water with various admixtures, can be used to achieve lower delivery temperatures, larger temperature differences, and thus smaller storage volumes per ton-hour (Andrepont 2000; Borer and Schwartz 2005).

When the stratified storage tank is charged, chilled supply water, typically between 38 and 44°F, enters through the diffuser at the bottom of the tank (Figure 1), and the warmer return water exits to the chiller through the diffuser at the top of the tank. Typically, incoming water mixes with water in the tank to form a 1 to 2 ft thick thermocline, which is a region with sharp vertical temperature and density gradients (Figure 2). The thermocline minimizes further mixing of the water above it with that below it. The thermocline rises as charging continues and subsequently falls during discharging. It may thicken somewhat during charging and discharging because of heat conduction through the water and heat transfer to and from the walls of the tank. The storage tank may have any cross section, but the walls are usually vertical. Horizontal cylindrical tanks are generally not good candidates for stratified storage, because of the ratio of the volume of water within and outside the thermocline.

Flexible Diaphragm. A flexible barrier, normally made from a rubber composition material, installed horizontally inside the water storage tank, separates the colder and warmer water. The diaphragm must be sized to float from the top of the tank to the bottom as the tank is fully charged to fully discharged. Potential for the diaphragm to hang up during travel through the tank and lost volume at the top and bottom of its travel reduce the effectiveness of this method.

Multiple Compartments or Multiple Tanks. Multiple compartments in a single tank or a series of two or more tanks can also be used for chilled-water storage. Water may flow through compartments in series, with opposite flow directions during charging and discharging. In empty tank systems, there is one more compartment than required to contain the full stored volume. During charging and discharging, one of the full compartments is emptied while the empty compartment is filled. This is done sequentially until charging or discharging is complete. Consequently, warmer and cooler water never occupy a tank at the same time. This procedure allows using horizontal or vertical tanks of any configuration and size; drawbacks are the complexity of controls and the need to have an empty tank.

Labyrinth Tank. This storage tank has both horizontal and vertical traverses. The design commonly takes the form of successive
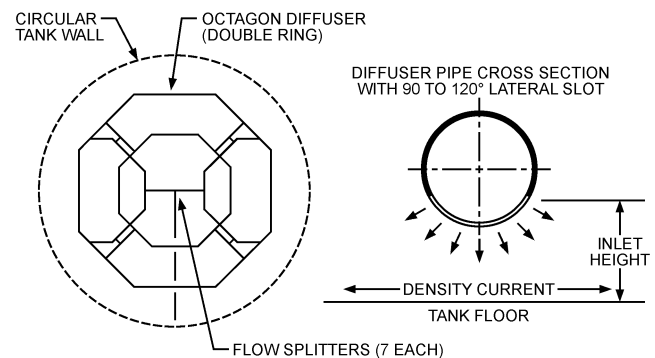
Fig. 1 Typical Two-Ring Octagonal Slotted Pipe Diffuser

cubicles with high and low ports, requiring the water to move from a high to a low port as the storage tank is being charged and the opposite as the tank is being discharged. Strings of cylindrical tanks and tanks with successive vertical weirs may also be used for this technique.

Performance of Chilled-Water Storage Systems

A perfect sensible storage device would deliver water at the same temperature at which it was initially stored. This would also require that water returning to storage neither mix with nor exchange heat with stored water in the tank or the surroundings of the tank. In practice, however, all three types of heat exchange occur.

Typical temperature profiles of water entering and leaving a storage tank are shown in Figure 3. Tran et al. (1989) tested several large chilled-water storage systems and developed the **figure of merit (FOM)**, which is used as a measure of the amount of cooling available from the storage tank.

$$\text{FOM} \ = \ \frac{\text{Area between } A \text{ and } C}{\text{Area between } A \text{ and } D} \times 100 \qquad (1)$$

Well-designed storage tanks have figures of merit of 90% or higher for daily complete charge/discharge cycles.

LIVE GRAPH
Click here to view
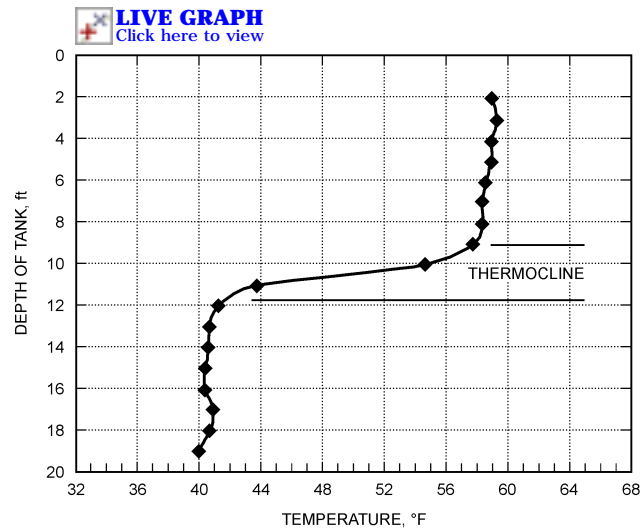
Fig. 2   Typical Temperature Stratification Profile in Storage Tank

LIVE GRAPH
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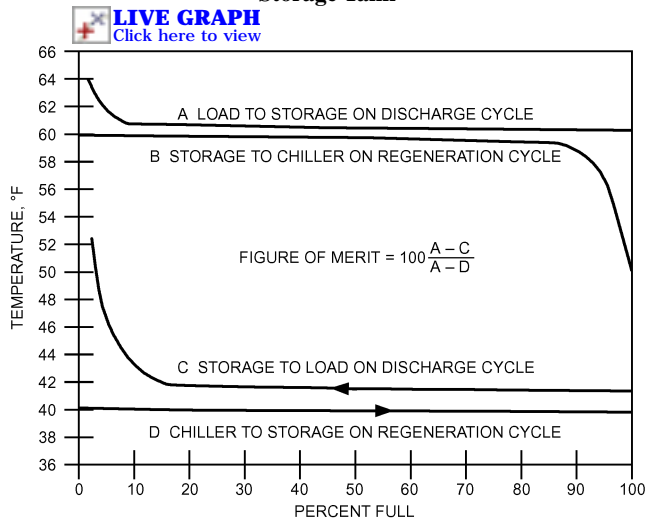
Fig. 3   Typical Chilled-Water Storage Profiles

Design of Stratification Diffusers

Diffusers must be designed and constructed to produce and maintain stratification at the maximum expected flow rate through storage. Two main styles are in widespread use today: the octagonal pipe diffuser (see Figure 1) and the radial disk diffuser (Figure 4). Inlet and outlet streams must be kept at sufficiently low velocities, so buoyancy predominates over inertia to produce a gravity current (density current) across the bottom or top of the tank.

The inlet Froude number Fr is defined as

$$\text{Fr} \ = \ \frac{Q}{\sqrt{gh^3(\Delta\rho/\rho)}} \qquad (2)$$

where

Q = volume flow rate per unit length of diffuser, ft^3/s·ft
g = gravitational acceleration, ft/s^2
h = inlet opening height, ft
ρ = inlet water density, lb/ft^3
$\Delta\rho$ = difference in density between stored water and incoming or outflowing water, lb/ft^3

The density difference $\Delta\rho$ can be obtained from Table 1. The inlet Reynolds number Re is defined as follows:

$$\text{Re} = Q/v \qquad (3)$$

where v = kinematic viscosity, ft^2/s.

Designers typically select values for Re, which determines the diffuser length, then select a value for the diffuser height to create an inlet Froude number of 1.0 or less. However, values up to 2.0 have been successfully applied (Yoo et al. 1986). Some experimental evidence indicates that the intensity of mixing near the inlet diffuser is influenced by the inlet Reynolds number [Equation (3)].

Wildin and Truman (1989), observing results from a 15 ft deep, 20 ft diameter vertical cylindrical tank, found that reduction of the inlet Reynolds number from 850 (using a radial disk diffuser) to 240 (using a diffuser comprised of pipes in an octagonal array) reduced mixing to negligible proportions. This is consistent with subsequent results obtained by Wildin (1991, 1996) in a 3 ft deep scale model

Table 1   Chilled-Water Density Table

°F	lb/ft^3	°F	lb/ft^3	°F	lb/ft^3
32	62.419	44	62.424	58	62.378
34	62.424	46	62.421	60	62.368
36	62.426	48	62.417	62	62.357
38	62.427	50	62.411	64	62.344
39	62.428	52	62.404	66	62.331
40	62.427	54	62.396	68	62.316
42	62.426	56	62.387		
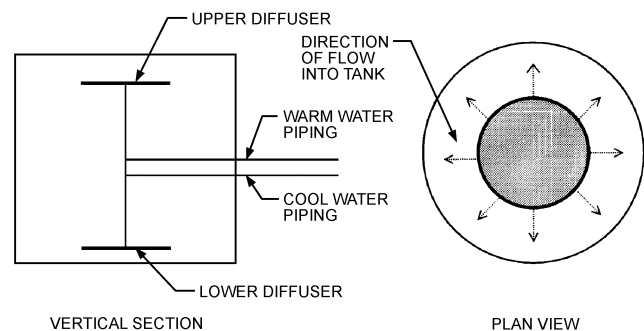
Fig. 4   Radial Disk Diffuser

tank, which indicated negligible mixing at Reynolds numbers below approximately 450, with the best performance achieved during testing at a Reynolds number of 250.

Bahnfleth and Joyce (1994), Musser and Bahnfleth (1998, 1999), and Stewart (2001) documented successful operation of tanks with water depths greater than 45 ft for design inlet Reynolds numbers as high as 10,000, although thermal performance of these systems improved at lower inlet Reynolds numbers.

A parametric study of radial diffusers by Musser and Bahnfleth (2001) found that using Froude numbers less than 1.0 significantly improved performance. Their work, based on field measurements and simulation, confirmed that the Froude number is a parameter of first-order significance for radial diffuser inlet thermal performance, but did not indicate strong effects of varying the Re. They found that parameters relating diffuser and tank dimensions (i.e., ratio of diffuser diameter to diffuser height and ratio of diffuser diameter to tank diameter) had a stronger effect on performance and could explain some of the behavior attributed to Re by earlier research. A similar study of octagonal diffusers by Bahnfleth et al. (2003a) also indicated that diffuser/tank parameters not previously used in design could be of greater significance than Re. They also concluded that diffuser/tank interaction parameters could be important factors in octagonal diffuser performance, and that radial and pipe diffusers are not well described by a single design method.

Because a chilled-water system may experience severe pressure spikes (water hammer), such as during rapid closing of control or isolation valves, the structural design of diffusers should consider this potential event. In addition, the diffusers themselves can also be subjected to buoyancy effects in the rare instance where air entrained in the chilled-water system becomes trapped in the piping and flows to the diffuser. Design considerations should be made to allow any trapped air to escape from the diffuser piping with little or no effect on diffuser performance.

Storage Tank Insulation

Exposed tank surfaces should be well insulated to help maintain the temperature differential in the tank. Insulation is especially important for smaller storage tanks because the ratio of surface area to stored volume is relatively high. Heat transfer between the stored water and tank contact surfaces (including divider walls) is a primary source of capacity loss. In addition to heat losses or gains by conduction through the floor and wall, heat flows vertically along the tank walls from the warmer to the cooler region. Exterior insulation of the tank walls does not totally inhibit this heat transfer.

The contents of chilled-water storage tanks are typically colder than the ambient dew-point temperature, so it is important that the insulation system use a high-integrity exterior vapor barrier to minimize ingress of moisture and condensation into the insulation system.

Other Factors

The cost of chemicals for water treatment may be significant, especially if the tank is filled more than once during its life. A filter system helps keep stored water clean. Exposure of stored water to the atmosphere may require the occasional addition of biocides. Although tanks should be designed to prohibit leakage, the designer should understand the potential effect of leakage on the selection of chemical water treatment. Water treatment based on requirements for a truly open system such as a condenser water system may be excessive, because water in a stratified tank is not aerated and is exposed to the atmosphere only through a small vent at the top of the storage tank. Owners should be careful to consider all factors involved when implementing a water treatment plan. The water treatment should be flexible based on the quantity of makeup water added to the system. See the Water Treatment section for more information.

The storage circulating pumps should be installed below the minimum operating water level of the lowest tank to ensure a continuously pressurized flooded suction. The required net positive suction head (NPSH) must be maintained to avoid cavitation of the pumps.

Chilled-Water Storage Tanks

Chilled-water storage systems are typically of large capacity and volume. As a result, many stratified chilled-water storage systems are located outdoors (e.g., in industrial plants or suburban campus locations). A tall tank is desirable for stratification, but a buried tank may be required for architectural, aesthetic, or zoning reasons. Tanks are typically constructed of steel or prestressed concrete to specifications used for municipal water storage tanks. Prestressed concrete tanks can be partially or completely buried below grade. For tanks that are completely buried, the tank roof can be free-standing dome type construction, or column-supported for heavy roof loads such as parking lots, tennis courts, or parks.

Low-Temperature Fluid Sensible Energy Storage

Low-temperature fluids (LTFs) may be used as a sensible cool storage medium instead of water. Using an LTF can allow sensible energy thermal storage at temperatures below 39.2°F, the temperature at which the maximum density of plain water occurs. Thus, LTFs can allow lower-temperature applications of sensible energy storage, such as for low-temperature air conditioning and some food processing applications. LTFs can be either aqueous solutions containing a chemical additive, or nonaqueous chemicals. A number of potential LTFs have been identified by Stewart (2000). One LTF has been in continuous commercial service in a stratified thermal storage tank in a very large district cooling system since 1994, and has exhibited good corrosion inhibition and microbiological control properties (Andrepont 2000, 2006).

Storage in Aquifers

Aquifers are underground, water-yielding geological formations, either unconsolidated (gravel and sand) or consolidated (rocks), that can be used to store large quantities of thermal energy. In general, the natural aquifer water temperature is slightly warmer than the local mean annual air temperature. Aquifer thermal energy storage has been used for process cooling, space cooling, space heating, and ventilation air preheating (Jenne 1992). Aquifers can be used as heat pump sinks or sources and to store energy from ambient winter air, waste heat, and renewable sources. For more information, see Chapter 32.

The thickness and porosity of the aquifer determine the storage volume. Two separate wells are normally used to charge and discharge aquifer storage. A well pair may be pumped either (1) constantly in one direction or (2) alternately from one well to the other, especially when both heating and cooling are provided. Backflushing is recommended to maintain good well efficiency.

The length of storage depends on the local climate and the type of building or process being supplied with cooling or heating. Aquifer thermal energy storage may be used on a short- or long-term basis, as the sole source of energy or as partial storage, and at a temperature useful for direct application or needing augmentation by boilers or chillers. It may also be used in combination with a dehumidification system, such as desiccant cooling. The cost effectiveness of aquifer thermal energy storage is based on the avoidance of equipment capital cost and on lower operating cost.

Aquifer thermal energy storage may be incorporated into a building system in a variety of ways, depending on the other components present and the intentions of the designer (CSA 1993; Hall 1993). Control is simplified by separate hot and cold wells that operate on the basis that the last water in is the first water out. This principle ensures that the hottest or coldest water is always available when needed.

Seasonal storage has a large savings potential and began as an environmentally sensitive improvement on the large-scale mining

of groundwater (Hall 1993). The current method reinjects all pumped water to attempt annual thermal balancing (Morofsky 1994; Public Works Canada 1991, 1992; Snijders 1992). Rock caverns have also been used successfully in a manner similar to aquifers to store energy. For example, Oulu, Finland, stores hot water in a cavern for district heating.

Latent Cool Storage Technology

Latent cool storage systems achieve most of their capacity from the latent heat of fusion of a phase-change material, although sensible heat contributes significantly to many designs. The high energy density of latent storage systems allows compact installations and makes factory-manufactured components and systems practical. Latent storage devices are available in a wide variety of distinct technologies that sometimes defy accurate classification. Current categories include internal-melt ice-on-coil, external-melt ice-on-coil, encapsulated, ice harvester, and ice slurry technologies.

A challenge common to all latent energy storage methods is to find an efficient and economical means of achieving the heat transfer necessary to alternately freeze and melt the storage medium. Various methods have been developed to limit or deal with the heat transfer approach temperatures associated with freezing and melting; however, leaving fluid temperatures (from storage during melting) must be higher than the freezing point, and entering fluid temperatures (to storage during freezing) must be lower than the freezing point. Ice storage can provide leaving temperatures well below those normally used for comfort and nonstorage air-conditioning applications. However, entering temperatures are also much lower than normal. Some PCM storage systems can be charged using temperatures near those for comfort cooling, but they produce warmer leaving temperatures.

Water as Phase-Change Thermal Storage Medium

An overwhelming majority of latent storage systems use plain water as the storage medium. A number of other materials have been developed over the years and are sometimes used in unique applications. However, water's combination of reliability, stability, insignificant cost, high latent heat capacity of 144 Btu/lb, high specific heat, high density, safety, and appropriate fusion temperature have proven desirable for many typical HVAC cooling applications.

Water has a very stable melting point of 32°F at sea level. Under some conditions, supercooling can depress the initial freezing point by 2 to 5°F, but impurities found in potable water, random disturbances, minor vibrations, surface interactions, or intentional agitation are generally sufficient to initiate nucleation of ice crystals. Supercooling most often occurs during an initial reduction of the liquid water temperature below 32°F. Residual ice reduces or eliminates the supercooling tendency for subsequent ice-making periods. The amount of supercooling, if experienced at all, is typically 2 or 3°F, and the phase-change temperature rapidly returns to 32°F immediately after this initial nucleation period. With relatively pure water that is isolated from any external influence, a proprietary agent may be used to induce nucleation.

Water slightly decreases in density below 39°F and expands by about 9% on freezing. This expansion is often used as an indicator of ice inventory where the ice remains completely submerged, such as with the ice-on-coil systems or ice-harvesting systems. If the ice is allowed to float in liquid water, the liquid level will remain constant as ice is frozen or melted. Ice slightly increases in density below the freezing temperature, but this is of little interest in storage systems, which all operate close to the phase-change temperature, and the variation is minor.

Many ice storage technologies use secondary coolants for heat transfer. This allows use of standard chillers, including centrifugals, for ice building and simplifies the application of the technology to typical chilled-water cooling systems. Common secondary coolants have well-documented properties and provide reliable freeze and corrosion protection when properly maintained and installed. The

proper concentration for the coolant is selected to provide a freeze point well below the lowest expected coolant temperature. This temperature is determined by the heat transfer characteristics of the storage device, flow rates, and chiller capacity.

Internal Melt Ice-On-Coil

Internal-melt ice-on-coil thermal storage devices circulate a secondary coolant or refrigerant through a tubular heat exchanger that is submersed in a cylindrical or rectangular tank of water. The phase-change water remains in the tank; both charging (ice making) and discharging (ice melting) are accomplished by circulating the secondary heat transfer fluid. Ice forms on the heat exchanger tubes during charging, and melts from the inside out (hence the term internal-melt) during discharging.

Internal-melt storage devices may be provided as complete, modular, factory-assembled units, or may consist of field-erected tanks equipped with prefabricated heat exchangers. Most current designs use secondary coolants (e.g., 25% ethylene glycol/75% water) as the heat transfer fluid.

Storage devices using refrigerant as the heat transfer fluid have also been developed for applications typically served by direct expansion equipment, such as residential and small commercial installations. However, these devices have not achieved wide commercial acceptance to date.

Storage device manufacturers typically provide performance data, including at least the average and final charging temperatures as a function of charging rate and flow. The average temperature is useful for selecting chiller capacity and estimating energy consumption. The lowest anticipated temperature is needed to establish chiller protection settings, specify coolant freeze protection requirements, and verify the capabilities of chiller selections, which is particularly important for centrifugal chillers. Glycols are currently the most commonly used secondary coolants, and design practices are conventional, with no exceptional material limitations other than the exclusion of galvanized steel for surfaces in contact with the heat transfer fluid. Proper application of some secondary coolants is addressed in Chapter 4 of the 2006 *ASHRAE Handbook—Refrigeration*.

The tubular heat exchanger is typically constructed of polyethylene or polypropylene plastic, or galvanized steel. Refrigerant-based systems may use copper. The heat exchanger typically occupies about 10% of the tank volume. Tube spacing is generally closer than in external-melt heat exchangers to compensate for the indirect heat exchange and the gradual development of a liquid annulus in the discharge mode. There is no need to maintain a liquid channel between individual tubes. The entire water volume between heat exchanger tubes is frozen. Approximately 9% of the tank volume, all above the heat exchanger, is reserved for expansion of the water as it freezes. Heat exchange surface does not usually extend into this expansion volume. If water is frozen in this area of the tank, subsequent melting may result in ice remaining in the expansion area, with voids forming around the heat exchange surfaces below. Some manufacturers provide means to prevent this possibility. Because the heat exchanger is prevented from floating, structurally or by its own weight, the rise in water level is proportional to the ice inventory. Level sensors can provide inventory information to the automatic control and/or energy management systems.

Several combinations of tanks and heat exchangers are available for secondary coolant systems. Cylindrical plastic tanks provide a combination of structure, water containment, and corrosion protection, and use a polyolefin heat exchanger, typically formed into a spiral configuration to conform to the tank shape. Structural steel tanks are usually rectangular; water containment can be achieved with either a metal or flexible liner. Steel tanks are often hot-dip galvanized for corrosion protection, and can use either galvanized steel or polyolefin heat exchangers.

Some care is required in the design of external piping because these are often modular systems, sometimes with large numbers of individual tanks arrayed in a variety of patterns. Reverse-return piping is often used to simplify balancing.

An important characteristic of the internal-melt design is the relationship between the charging and discharging processes (Figure 5). During discharge, ice in contact with the heat exchanger is melted first. Initial discharge rates can be very high, and initial available temperatures approach the phase-change temperature. However, as ice melts, an annulus of water develops between the heat exchanger and ice surfaces. This results in variable performance for the internal-melt design. Manufacturers have developed various methods of incorporating the effect of ice inventory levels in product performance descriptions. The temperature of coolant leaving the storage device varies with flow rate, supply temperature, and ice inventory. A mixing or diverting valve is often included to automatically adjust flow through the storage device, controlling both the leaving temperature and discharge rate. Because the storage flow can be completely independent of the chiller flow, cooling load can be imposed on either component in any desired proportion, allowing the designer to optimize discharge of storage for a particular utility rate and building load.

When the internal-melt system returns to ice-making (charging) mode, ice first forms directly on the heat exchanger surface and gradually accumulates, perhaps to a point where it joins with ice remaining from previous charges. Chilled-coolant temperatures are always at their most efficient levels for every ice-building period, and every charge can be carried to completion without penalty. There is usually no benefit to limiting the amount of ice produced, so the storage can be fully charged every night. Because the internal storage temperature is always at the phase-change temperature, standby losses are virtually independent of ice inventory. This simplifies control logic, maximizes efficiency, and eliminates the potential liabilities of predicting the next day's required storage. The close tube spacing needed for good discharge performance provides excellent ice-making performance, because the thermal conductivity of ice is about 3.5 times greater than that of liquid water. Although coolant temperatures depend on many factors, a typical charge cycle begins with coolant temperatures of 26°F entering storage and leaving near 32°F. For most of the charge period, the coolant temperatures are fairly stable, gradually diminishing but with an average supply temperature of approximately 24°F. As the end of the charge mode nears, temperatures decrease at much faster rates to perhaps a minimum supply temperature of 22°F. The rapid temperature decrease at the end of the charge cycle is caused by the exhaustion of latent heat and the lower specific heat of ice compared to liquid water. Depending on system type, a full charge may be indicated by an inventory measurement or a final leaving temperature. The ice-making chiller or compressor is generally fully loaded throughout the ice-making period. Once the ice inventory is completely restored, ice-making chiller operation is terminated to prevent cycling the chiller in the ice-making mode.
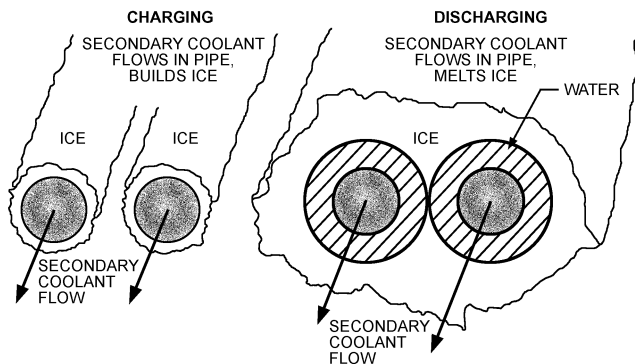
External-Melt Ice-On-Coil

External-melt ice-on-coil thermal storage devices also consist of a tubular heat exchanger submersed in a cylindrical or rectangular tank of water. However, these devices circulate a secondary coolant through the tubes only for charging. Discharging is accomplished by circulating the water surrounding the heat exchanger. Ice melts from the outside in (Figure 6).

Traditional external-melt storage devices build ice by circulating cold liquid refrigerant through the heat exchangers. Although this approach is still commonly used in industrial applications, most external-melt systems for HVAC applications currently use glycol secondary coolants for charging. Water surrounding the heat exchanger is both the phase-change material and the heat transfer fluid for the discharge mode.

The charging heat transfer fluid is contained in a separate circuit from the water in the storage tank. Typically, a heat exchanger is installed between the two circuits to allow the same chiller to charge storage and help meet the cooling load directly. Some designs use separate chillers, or two separate evaporators served by the same compressor, to fulfill these functions. It is also possible to simply continue to circulate the heat transfer fluid through the storage heat exchanger to assist in direct cooling, but this approach requires that the refrigeration equipment continuously operate at subfreezing temperatures, incurring substantial capacity and efficiency penalties.

The individual galvanized steel heat exchangers or coils are assembled from a number of separate tubing circuits, and are usually stacked into large, site-fabricated concrete tanks. The tanks operate at atmospheric pressure, and additional measures may be needed to accommodate pressurized systems or elevation differences. The heat exchanger tube cross section can be circular or elliptical. Many different coil lengths, widths, and heights are available to conform to tank dimensions while simplifying coil connections, providing desired flow and pressure drop, and minimizing shipping costs.

Some form of agitation is needed to promote even ice building and melting, although continuous agitation may not be necessary during charging. Agitation is usually provided by distributing compressed air through plastic pipes under of each stack of heat exchangers.

The annular thickness of ice formed on the heat exchanger can vary widely, but an average of about 1.4 in. is a typical dimension used in published ratings. Proper ice-making control is particularly important for external melt systems. Ice-making temperatures are driven lower by excessive ice thickness. Because any new ice must be formed on the surface of existing ice, there is a benefit to limiting the ice thickness to what is needed for the following discharge period, while still ensuring an adequate storage inventory. Also, ice bridging must be prevented. A flow passage of liquid water must be

Fig. 5   Charge and Discharge of Internal-Melt Ice Storage
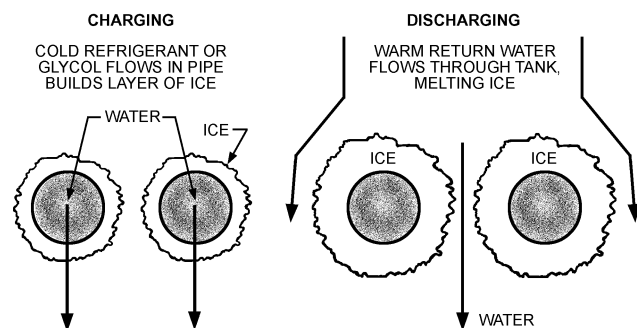
Fig. 6   Charge and Discharge of External-Melt Ice Storage

preserved between adjacent circuits of ice-building coils. Once flow is stopped or restricted, the ability to melt any ice can be significantly limited. Maintaining minimum ice inventory levels discourages ice bridging and promotes efficiency. Ice thickness controllers that sense a change in electrical conductivity are commonly used to control ice building, but other types are available. Manufacturers specify the number and location of thickness controllers. Continuous inventory measurement can be obtained by load cells or strain gages that measure the weight of the ice and steel coils, multiple thickness sensors, or by the change in water level, compensating for compressed air introduced into the tank.

Because the storage tank is at atmospheric pressure, some method may be needed to connect to a higher-pressure distribution water loop. The simplest methods are locating the tank at the highest elevation or adding a chilled-water heat exchanger. Adding pressure-sustaining valves on the tank return or regenerative turbine pumping are other possibilities.

The wider coil spacing typical of external-melt heat exchangers results in lower ice-making temperatures than in internal-melt systems. However, the direct-contact heat exchange in melting provides consistently low chilled-water temperatures of approximately 34°F and high discharge rate capacity. Separate flow circuits for the chiller and storage provide flexibility in assigning cooling load to each device in any desired proportion.

Encapsulated Ice

Encapsulated storage systems use a phase-change material, usually water, contained in relatively small polymeric vessels. A large number of these primary containers are placed in one or more tanks through which a secondary coolant circulates, alternately freezing and melting the water in the smaller containers. Standard chillers are typically used for ice production.

Currently available shapes are basically spherical and are factory-filled with water and a nucleating agent. The sealed containers are shipped to the installation site, where they are placed into the insulated tank, occupying perhaps 60% of the internal tank volume. There is usually no attempt to position the containers in their most compact configuration, instead relying on simple random packing. Some designs have additional surface features. One product uses a 4 in. diameter sphere with deformable depressions or concave hollows arrayed around the surface (Figure 7). Liquid water fills virtually the entire internal volume with the hollows in a depressed position. As water is frozen and expands, the depressions shift from concave to convex. They return to the original shape as the water
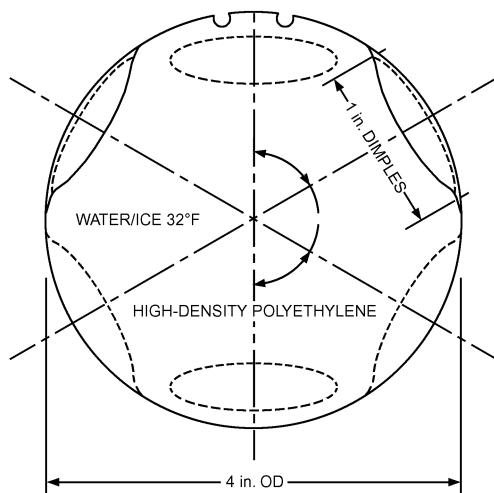
Fig. 7   Encapsulated Ice: Spherical Container
(Courtesy Cryogel)

melts. Besides accommodating water expansion, the variable-volume shape displaces the surrounding coolant. Displaced coolant can be used to measure ice inventory. For pressurized tanks, an additional expansion tank is included for this purpose; atmospheric tanks use the change in the coolant level for the primary tank as an inventory indicator. Other products use a more rigid shape and accommodate water expansion by leaving a void space within the container. Systems with rigid spheres use an energy balance method for inventory determination. Spheres with base diameters of 3 to 4 in. are available. The spheres are buoyant when surrounded by the secondary coolant. A third method, recently introduced, uses an internal collapsible chamber in a 5.4 in. sphere to accommodate expansion.

A wide variety of vertical and horizontal tanks, both pressurized and atmospheric, can be used. Internal headers are designed to distribute flow evenly throughout the storage volume. Some tanks can be completely buried. Atmospheric tanks must have a grid near the top of the tank to prevent flotation of the buoyant water-filled spheres. Although requiring more heat transfer fluid, the large cross sectional flow area results in low pressure drops of approximately 7 to 9 feet.

Charging and discharging are similar to internal-melt ice-on-coil systems, using similar secondary coolants (e.g., 25% ethylene glycol/75% water). Flow typically proceeds through the tank from bottom to top. As with internal-melt systems, the temperature of coolant leaving the storage device varies with flow rate, supply temperature, and ice inventory. Because the shape and volume of the storage tanks varies over a wide range, manufacturers often provide performance data on a per-ton-hour basis.

Ice Harvesters

Ice-harvesting systems separate the formation of ice from its storage. Ice is generated by circulating 32°F water from the storage tank over the surfaces of plate or cylindrical evaporators arranged in vertical banks above the storage tank. Ice is typically formed to a thickness between 0.25 and 0.40 in. over a 10 to 30 min build cycle. The ice is harvested by a hot-gas defrost cycle, which melts the bond between the ice and the evaporator surface and allows the ice to drop into the storage tank below. Other types of ice harvesters separate ice from the evaporator surface mechanically.

Typically, the evaporators are grouped in sections that are defrosted individually so that the heat of rejection from active sections provides the energy for defrost. Tests done by Stovall (1991) indicate that, for a four-section plate ice harvester, the total heat of rejection is introduced into the evaporator during the defrost cycle. To maximize efficiency and ice production capacity, harvest time should be kept to a minimum.

Figure 8 shows an ice-harvesting schematic. Chilled water is pumped from the storage tank to the load and returned to the ice generator. A low-pressure recirculation pump is used to provide minimum flow for wetting the evaporator in ice-making mode. This system may be applied to load-leveling or load-shifting applications.

In load-leveling applications, ice is generated and the storage tank charged when there is little or no building load. When a building load is present, the return chilled water flows directly over the evaporator surface, and the ice generator functions either as a chiller or as both an ice generator and a chiller. The defrost cycle is energized if the return water temperature is low enough that the exit water from the evaporator is within a few degrees of freezing. When operated as a chiller only, maximum capacity and efficiency are obtained with minimum water flow and highest entering water temperature. In load-shifting applications, the compressors are turned off during the utility company's on-peak period, and ice water from the tank is circulated to the building load.

During the first part of the charge cycle, ice floats in the tank with about 10% of its volume above the water, and the water level remains constant. As ice continues to build, the ice comes to rest on
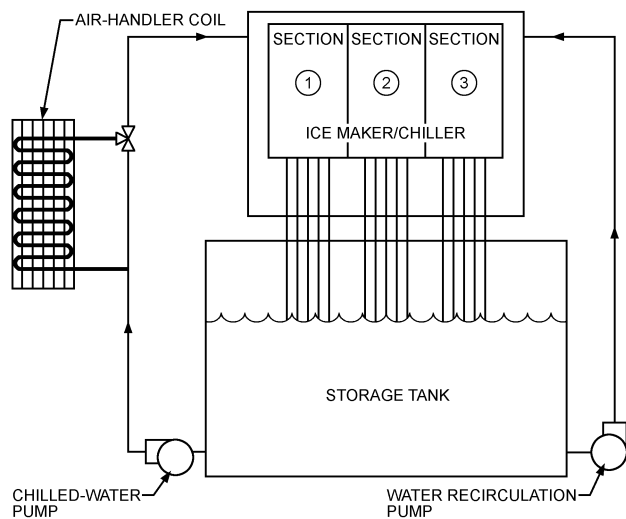
Fig. 8 Ice-Harvesting Schematic
(Courtesy Paul Mueller Company)

the bottom of the tank and builds up above the water level. The ice generation mode is terminated when the ice reaches the high ice level, as determined by a mechanical, optical, or electronic high-level sensor.

Because the ice is free to float in the tank, ice inventory cannot be determined by measuring the water level. Ice inventory may be tracked by maintaining a running energy balance calculation that monitors cooling discharged from and stored in the tank. The amount of cooling discharged can be determined by measuring chilled-water flow rate and supply and return temperatures. Cooling stored in the tank can be measured as the difference between the energy input to the compressor and the heat rejection from the condenser, or estimated based on compressor performance data and operating conditions. Ice inventory may also be tracked by measuring changes in water conductivity as the ice freezes and melts.

Although tank water level cannot be used to indicate the ice inventory during the storage cycle, the water level at the end of charging is a good indicator of system conditions. In systems with no gain or loss of water, the shutdown level should be consistent, and can be used as a back-up to determine when the tank is full for shutdown requirements. Conversely, a change in level at shutdown can indicate a water gain or loss.

Ice harvester systems usually use positive-displacement compressors with saturated suction temperatures usually between 18 and 22°F. The condensing temperature should be kept as low as possible to reduce energy consumption. The minimum allowable condensing temperature depends on the type of refrigeration used and the system's defrost characteristics. Several systems operating with evaporatively cooled condensers have operated with a compressor specific power consumption of 0.9 to 1.0 kW/ton (Knebel 1986, 1988; Knebel and Houston 1989).

Ice-harvesting systems can discharge stored cooling very quickly. Individual ice fragments are characteristically less than 6 by 6 by 0.25 in. and provide a large surface area per ton-hour of ice stored. When properly wetted, a 24 h charge of ice can be melted in less than 30 min for emergency cooling demands.

Ice harvesters typically use field-built concrete tanks or prefabricated steel tanks. The thermal storage capacity of usable ice that can be stored in a tank depends on its shape, location of the ice entrance to the tank, angle of repose of the ice (between 15 and 30°, depending on the shape of ice fragments), and water level in the tank. If the water level is high, voids occur under the water because of the ice's buoyancy. The ice harvester manufacturer may assist in tank design and piping distribution in the tank. Gute et al. (1995)

and Stewart et al. (1995a, 1995b) describe models for determining the amount of ice that can be stored in rectangular tanks and the discharge characteristics of various tank configurations. Dorgan and Elleson (1993) provide further information.

The tank may be completely or partially buried or installed above ground. A minimum of 2 in. of closed-cell insulation should be applied to the external surface. Because shifting ice creates strong dynamic forces, internal insulation should not be used except on the underside of the tank cover, and only very rugged components should be placed inside the tank. Exiting water distribution headers should be constructed of stainless steel or rugged plastic suitable for the cold temperatures encountered. PVC is not an acceptable material because of its extreme brittleness at the ice-water temperature.

As with field-built concrete tanks for other storage applications, close attention to design and construction is important to prevent leakage. An engineer familiar with concrete construction requirements should monitor each pour and check all water stops and pipe seals. Unlined tanks that do not leak can be built. If liners are used, the ice equipment suppliers will provide assistance in determining a suitable type, and the liner should be installed only by a qualified installer trained by the liner manufacturer.

The sizing and location of the ice openings are critical; all framed openings must be verified against the certified drawings before the concrete is poured.

An ice harvester is generally installed by setting in place a prepackaged unit that includes the ice-making surface, refrigerant piping, refrigeration equipment, and, in some cases, heat rejection equipment and prewired controls. To ensure proper ice harvesting, the unit must be properly positioned relative to the ice drop opening. The internal piping is not normally insulated, so the drop opening should extend under the piping so condensate drops directly into the tank. A grating below the piping is desirable. To prevent air or water leakage, gasketing and caulking must be installed in accordance with the manufacturer's instructions. External piping and power and control wiring are required to complete the installation.

Ice Slurry Systems

Ice slurry is a suspension of ice crystals in liquid. An ice slurry system has the advantage of separating production of ice from its storage without the control complexity and efficiency losses associated with the ice harvester's defrost cycle. Slurries also offer the possibility of increased energy transport density by circulating the slurry itself, rather than just the circulating secondary liquid. However, a heat exchanger is usually used to separate the storage tank flow from the cooling load distribution loop. Like harvesters, slurry systems have very high discharge rates and provide coolant consistently close to the phase-change temperature.

In general, the working fluid's liquid state consists of a solvent (water) and a solute such as glycol, sodium chloride, or calcium carbonate. Depending on the specific slurry technology, the initial solute concentration varies from 2% to over 10%, by mass. The solute depresses the freezing point of the water and buffers the production of ice crystals. Slurry generation begins by lowering the temperature of the working fluid to its initial freezing point. Upon further cooling, water begins to freeze out of the solution. As freezing progresses, the concentration of solute increases and the freezing point at which ice crystals are produced decreases. Ice/water slurries have been reported to have a porosity of 0.50 and typical storage densities of 2.92 ft³/ton·hour (Gute et al. 1995).

One design uses a 7% solution of propylene glycol that provides an initial freezing temperature of about 28°F. A final freezing point of 25°F indicates that a full charge has been reached and about 50% of the volume has been frozen. Ice is formed near the inside surfaces of multiple cylinders of the orbital rod evaporator. Rotating rods travel along the inner evaporator surfaces, creating an agitated flow that enhances heat transfer and prevents adhesion of ice crystals. The compliant method of connecting the rod prevents damage in the

event of evaporator freeze-up. This arrangement reduces or eliminates the need for a defrost cycle, but adds mechanical components. The evaporators are typically arranged in vertical banks above the storage tank, and the slurry can also be pumped into an adjoining tank.

Other Phase-Change Materials

Water now dominates the market as the storage material for HVAC applications, but industrial or commercial processes sometimes require coolant temperatures that are not possible using plain water. A substantial amount of effort has been invested in the development of materials that would freeze above 32°F and still provide appropriate temperatures in the discharge mode. There are currently no commercially available systems using these materials. Phase-change materials with fusion temperatures above 32°F were usually inorganic salt hydrates that had high anhydrous salt fractions and limited latent heat capacities.

Materials with fusion temperatures below 32°F are more practical to develop and apply. These are often true salt eutectics and typically require lower percentages of the anhydrous components than materials with fusion temperatures above 32°F. Container geometry, or some chemical or mechanical means, prevents eventual stratification of components. Because these materials have salt constituents, they are more corrosive than plain water and are currently only available in encapsulated or all-plastic internal-melt ice-on-coil devices. The latent heat capacities for these materials are usually close to the volumetric heat capacities available from plain water. Supercooling is frequently associated with eutectics and hydrates and appropriate nucleating agents are often added to the material.

Unfortunately, storage at subfreezing temperatures cannot be achieved by adding a freeze depressant, such as ethylene glycol, to water. Unless the additive exists at a eutectic concentration, only the initial freezing point is affected, with the temperature gradually decreasing as the freezing process continues (see the section on Ice Slurry Systems). In most cases, the loss in volumetric heat capacity for a useful range of storage charge and discharge temperatures makes this an impractical solution.

HEAT STORAGE TECHNOLOGY

The most common current application of heat storage is in electrically charged, thermally discharged storage devices used for service water heating and space heating. Thermal storage systems for space heating can be classified as brick storage heaters (electric thermal storage or ETS heaters), water storage heaters, or radiant floor heating systems. Other applications include solar space and water heating, and thermally charged water storage tanks.

The choice of storage medium generally depends on the type of heating system. Air heaters use brick as the storage medium, whereas water heaters may use water or a PCM. Combination brick and hydronic systems use brick for the storage medium and transfer the heat to water as needed.

Solar space and water heating systems use rock beds, water tanks, or PCMs to store heat. Various applications are described in Chapter 33 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*.

Thermally charged hot-water storage tanks are similar in design to the cool storage tanks described in the section on Storage of Heat in Cool Storage Units. Many are also used for cooling. Unlike off-peak cooling, off-peak heating seldom reduces the size of the heating plant or the utility bill (except in the case of collecting waste heat, such as applications associated with industrial processes or a turbine generator). The size of a storage tank used for both heating and cooling is based more on cooling than on heating for lowest life-cycle cost, except in some residential applications.

Sizing Heat Storage Systems

For electrically charged devices that use a solid mass as the storage medium, equipment size is typically specified by the nominal power rating (to the nearest kilowatt) of the internal heating elements. The nominal storage capacity is taken as the amount of energy supplied during an 8 h charge. For example, a 5 kW heater would have a nominal storage capacity of 40 kWh. ASHRAE *Standard* 94.2 describes methods for testing these devices. If multiple charge/off-peak periods are available during a 24 h period, an alternative method that considers not only the nominal power rating, but also fan discharge rate and storage capacity, yields a more accurate estimate of equipment size. Consult the equipment manufacturer for more information on calculating the capacity of these devices.

A rational design procedure requires an hourly simulation of the design heat load and a known discharge capacity of the storage device. The first criterion for satisfactory performance is that the discharge rate must be no less than the design heating load at any hour. During the off-peak period, energy is added to storage at the rate determined by the connected load of the resistance elements less the design heating load. The second criterion for satisfactory performance is that energy added to storage during one day's off-peak period is sufficient to meet the total load for the entire 24 h.

A simplified procedure is recommended by Hersh et al. (1982) for typical residential designs. For each zone of the building, the design heat loss is calculated in the usual manner and multiplied by the selected sizing factor. The resulting value (rounded to the next kilowatt) is the required storage heater capacity. Sizing factors in the United States range from 2.0 to 2.5 for an 8 h charge period and from 1.6 to 2.0 for a 10 h charge period. If multiple off-peak periods occur during a 24 h period, this method may not accurately reflect equipment sizing. The designer should consult the manufacturer for specific sizing information based on on-peak and off-peak hours available. Figure 9 shows a typical sizing factor selection graph for an application that has a single charging time block per day.

Service Water Heating

The tank-equipped service water heater, which is the standard residential water heater in North America, is a thermal storage device, and some electric utilities provide incentives for off-peak water heating. To meet that requirement, the heater is equipped with

LIVE GRAPH
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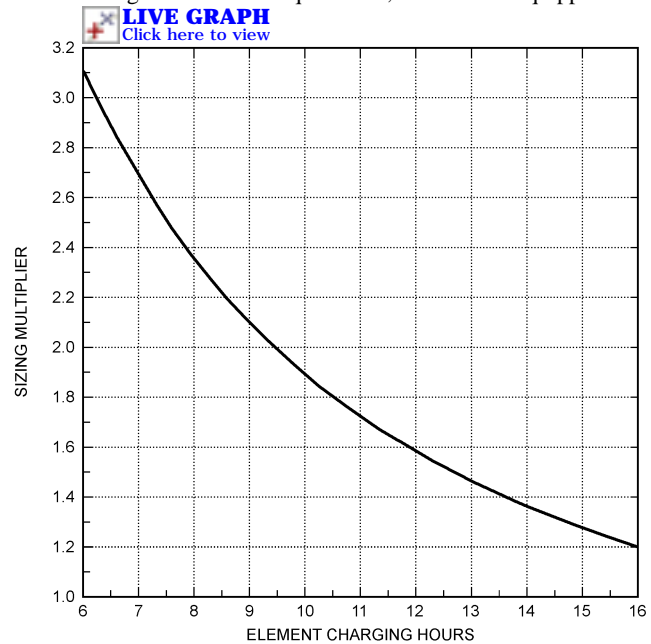
Fig. 9   Representative Sizing Factor Selection Graph for Residential Storage Heaters

a control system that is activated by a clock or by a signal directly from the electric utility to curtail power use during peak demand. An off-peak water heater generally requires a larger tank than a conventional water heater.

An alternative system of off-peak water heating consists of two tanks connected in series, with the hot-water outlet of the first tank supplying water to the second tank (ORNL 1985). This arrangement minimizes mixing of hot and cold water in the second tank. Tests performed on this configuration show that it can supply 80 to 85% of rated capacity at suitable temperatures, compared to 70% for a single-tank configuration. The wiring for the heating elements in the two tanks may have to be modified to accommodate the dual-tank configuration.

Brick Storage (ETS) Heaters

Brick storage heaters [commonly called electric thermal storage heaters (ETS)] are electrically charged and store heat during off-peak times. In this storage device, air circulates through a hot brick cavity and then discharges into the area in which heat is desired. The ceramic brick has a very dense magnetite or magnesite composition. The brick's high density and ability to store heat at a high temperature gives the heater a larger thermal storage capacity. Ceramic brick can be heated to approximately 1400°F during off-peak hours by resistance heating elements. Space requirements for brick storage heaters are usually much less than for other heat storage media.

Figure 10 shows the operating characteristics of an electrically charged room storage heater. Curve 1 represents theoretical performance with no discharge. In reality, radiation and convection from the exterior surface of the device continually supplies heat to the room during charging as well. Curve 2 shows this static discharge. When the thermostat calls for heat, the internal fan operates. The resulting faster dynamic discharge corresponds to curves 3 and 4. Because the heating elements of electrically charged room storage heaters are energized only during off-peak periods, they must store the total daily heating requirement during this period. The dynamic and static charging and discharging rates vary by equipment manufacturer.

The four types of brick storage heaters currently available are room storage heaters (room units), heat pump boosters, central furnaces, and radiant hydronic (brick to water).

Room Storage Heaters (Room Units). Room storage heaters (commonly called room units) have magnetite or magnesite brick cores encased in shallow metal cabinets (Figure 11). The core can be heated to 1400°F during off-peak hours by resistance heating elements located throughout the cabinet. Room units are generally small heaters that are placed in a particular area or room. These heaters have well-insulated storage cavities, which help retain the heat in the brick cavity. Although the brick inside the units gets very hot, the outside of the heater is relatively cool, with surface temperatures generally below 165°F. Storage heaters are discharged by natural convection, radiation, and conduction (static heaters) or, more commonly, by a fan. Air flowing through the core is mixed with room air to limit the outlet air temperature to a comfortable range.

Storage capacities range from 13.5 to 60 kWh. Inputs range from 0.8 to 10.8 kW. In the United States, 120, 208, 240, and 277 V units are commonly available. The 120 V model is useful for heating smaller areas or in geographical areas with moderate heating days. Room storage heaters are used in residential and commercial applications, including motels, hotels, apartments, churches, courthouses, and offices. Systems are used for both new construction and retrofit applications. A common commercial application is replacement of an aging boiler or hot-water heating system.

Operation is relatively simple. When a room thermostat calls for heat, fans in the lower section of the room unit discharge air through the ceramic brick core and into the room. Depending on the charge level of the brick core, a small amount of radiant heat may also be delivered from the surface of the unit. The amount of heat stored in the brick core of the unit can be regulated either manually or automatically in relation to the outside temperature or the known or estimated space requirements.

These units fully charge in about 7 h (Figure 12), and they can be fully depleted in as little as 5 h. The equipment retains heat for up to 72 h, if it has no fan discharge (Figure 13).
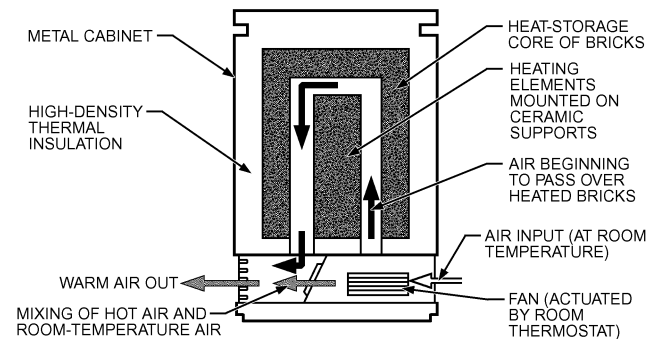
Fig. 11   Room Storage Heater
(Courtesy Steffes Corporation)

Fig. 12   Room Storage Heater Dynamic Discharge and Charge Curves

Fig. 10   Typical Storage Heater Performance Characteristics
(Hersh et al. 1982)

Choosing the appropriate size of room unit(s) depends on the length of the applicable on-peak and off-peak periods, local climate, and heat loss of the area or space. The designer must follow generally accepted practices for calculating design load or heat loss rate to ensure a properly functioning system that delivers satisfactory results. This equipment is generally configured according to one of the following two concepts:

Whole-House Concept. Under this strategy, room units are placed throughout the home. Units are sized according to a room-by-room heat loss calculation. This method is used in areas with long on-peak periods, generally 12 h or more.

Warm-Room Concept. Under this strategy, one or two room units are used as the primary heating source during on-peak periods. Units are placed in the area most often occupied (main area). Adjacent areas generally are kept cooler and have no operable heating source during the on-peak period; however, some heat migrates from the warmer main area.

When determining the heat loss of the main area, an additional sizing factor of approximately 25% should be added to allow for migration of heat to adjacent areas. Under the warm-room concept, sizing factors vary, depending on the rate structure of the power company and equipment performance under those conditions. Consult the equipment manufacturer for specific sizing information.

The warm-room concept is the most common method used by power companies for their load management and off-peak marketing programs. It is successful in areas that have a small number of consecutive hours of control (generally less than 12 h of on-peak time), or have a midday block of off-peak time during which the equipment can recharge. The advantage of the warm-room concept is that it requires smaller equipment and fewer heating units than the whole-house concept, thereby reducing system cost.

Heat Pump Boosters. Air-to-air heat pumps generally perform well when outside temperatures are relatively warm; however, as the outside temperature decreases, the efficiency, output capacity, and supply air temperature from a heat pump also decline. When the output of the heat pump drops below the heat loss of the structure, supplemental heat, typically from an electric resistance unit, must be added to maintain comfort. To eliminate the use of direct electric resistance heat during on-peak periods, storage heaters, such as the heat pump boosters (HPBs), can supplement the output of a heat pump. Additionally, the HPB monitors supply air temperatures and adds heat to the supply air as needed to maintain comfortable delivery air temperature at all times. The HPB can also be used as a booster for stand-alone forced-air furnaces or to back up electric or fossil fuel equipment in dual-fuel programs.
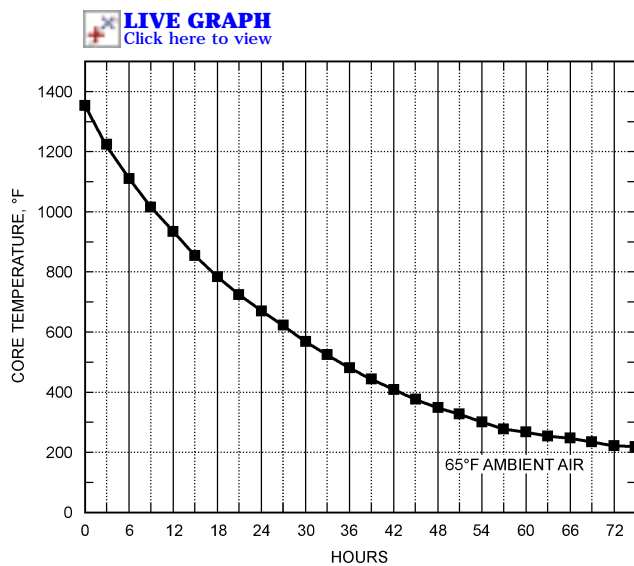
Core charging of the HPB is regulated automatically based on outdoor temperature. The brick storage core is well insulated so radiant or static heat discharge is minimal. Common residential equipment input power ratings range from 14 to 46 kW. Storage capacities range from 86 to 240 kWh. Larger commercial and industrial sizes have input ratings of 53 to 160 kW and storage capacities of up to 960 kWh.

Central Furnace. A central storage furnace is a forced-air heat storage product for residential, commercial, and industrial applications. These units are available with input ratings ranging from 14 to 46 kW. Storage capacities range from 86 to 960 kWh.

Radiant Hydronic Heaters. A ceramic brick storage system is available that uses an air-to-water heat exchanger to transfer heat from the storage system to a water loop. The off-peak heated water can be used in conventional hot-water systems, including floor warming (radiant floors), hydronic baseboards, hot-water radiators, indirect domestic hot-water heating, etc. An air handler can be added to these systems to achieve hydronic and forced-air heating from the same unit. In commercial and industrial applications, these systems can be used to preheat incoming fresh air in makeup air systems. These units are available in input ratings ranging from 20 to 46 kW with storage capacities from 120 to 240 kWh.

Pressurized Water Storage Heaters

This storage device consists of an insulated cylindrical steel tank containing immersion electrical resistance elements near the bottom of the tank and a water-to-water heat exchanger near the top (Figure 14). During off-peak periods, the resistance elements are sequentially energized until the storage water reaches a maximum temperature of 280°F, corresponding to 50 psig. The *ASME Boiler Code* considers such vessels unfired pressure vessels, so they are not required to meet the provisions for fired vessels. The heaters are controlled by a pressure sensor, which minimizes problems that could be caused by unequal temperature distribution. A thermal controller gives high-limit temperature protection. Heat is withdrawn from storage by running service water through the heat exchangers and a tempering device that controls the output temperature to a predetermined level. The storage capacity of the device is the sensible heat of water between 10°F above the desired output water temperature and 280°F. The output water can be used for space heating or service hot water. The water in the storage tank is permanently treated and sealed, requires no makeup, and does not interact with the service water.

In most applications, electrically charged pressurized water storage tanks must be able to be recharged during the off-peak period to meet the full daily heating requirement, while supplying heat to

Fig. 13 Static Discharge from Room Storage Heater
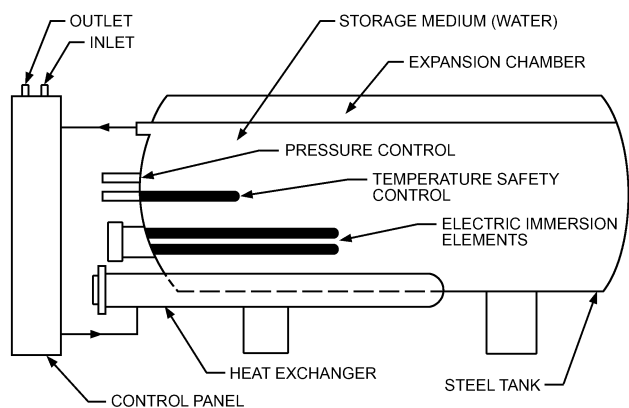
Fig. 14 Pressurized Water Heater

meet the load during the on-peak period. The heat exchanger design allows a constant discharge rate, which does not decrease near the end of the cycle.

Underfloor Heat Storage

This storage method typically uses electric resistance cables or hydronic tubing buried in a bed of sand 1 to 3 ft below the concrete floor of a building. Underfloor heat storage is suitable for single-story buildings, such as residences, churches, offices, factories, and warehouses. An underfloor storage heater acts as a flywheel. Although the unit is charged only during the nightly off-peak period, it maintains the top of the floor slab at a constant temperature slightly higher than the desired space temperature. Because the cables spread heat in all directions, they do not have to cover the entire slab area. For most buildings, a cable or tube location of 18 in. below the floor elevation is optimum. The sand bed should be insulated along its perimeter with 2 in. of rigid, closed-cell foam insulation, to a depth of 4 ft (Figure 15). Even with a well-designed and well-constructed underfloor storage, 10% or more of the input heat may be lost to the ground.

Building Mass Thermal Storage

The thermal storage capabilities inherent in the mass of a building structure can have a significant effect on the temperature in the space as well as on the performance and operation of the HVAC system. Effective use of structural mass for thermal storage reduces building energy consumption and reduces and delays peak heating and cooling loads (Braun 1990). In some cases, it improves comfort (Morris et al. 1994; Simmonds 1991). Perhaps the best-known use of thermal mass to reduce energy consumption is in buildings that include passive solar techniques (Balcomb 1983).

Cooling energy can be reduced by precooling the structure at night using ventilation air. Andresen and Brandemuehl (1992), Braun (1990), and Ruud et al. (1990) suggested that mechanical precooling of a building can reduce and delay peak cooling demand; Simmonds (1991) suggested that the correct building configuration may even eliminate the need for a cooling plant. Mechanical precooling may require more energy use; however, the reduction in electrical demand costs may give lower overall energy costs. Moreover, the installed capacity of air-conditioning equipment may also be reduced, providing lower installation costs. Braun (2003) provided an overview of related research, and found that (1) there is a tremendous opportunity for reductions in on-peak energy and peak

demand, and (2) the savings potential is very sensitive to the utility rates, building and plant characteristics, weather conditions, and occupancy schedule.

The potential energy cost savings from precooling depends on the control strategies used to charge and discharge the building thermal mass. Several studies of building pre-cooling controls have been reported (Braun 1990; Braun et al. 2001; Conniff 1991; Keeney and Braun 1996; Morgan and Krarti 2006; Morris et al. 1994; Rabl and Norford 1991; and Ruud et al. 1990). Precooling's potential in reducing electric energy costs is generally well documented. Reported investigations have shown that energy costs have been reduced by 10 to 50% under dynamic rates, and on-peak demand reduced by 10 to 35%, just by precooling building thermal mass.

In particular, Morgan and Krarti (2006) performed both simulation analyses and field testing to evaluate various precooling strategies. They found that the energy cost savings associated with precooling thermal mass depend on several factors, including thermal mass level, climate, and utility rate. For time-of-use utility rates, they found that energy cost savings are affected by the ratio of on-peak to off-peak demand charges R_d, as well as ratio of on-peak to off-peak energy charges R_e. Figures 16 and 17 show the variation of the annual energy cost savings from 4 h precooling an office building with heavy mass as a function of R_d and R_e, respectively.

Henze et al. (2004, 2005) and Kintner-Meyer and Emery (1995) evaluated the combined use of both building thermal mass (passive TES) and ice or chilled-water storage tanks (active TES), a load management strategy to shift on-peak building HVAC cooling load to off-peak time. Thermal mass use can be considered incidental and not be considered in the heating or cooling design, or it may be intentional and form an integral part of the design. Effective use of building structural mass for thermal energy storage depends on factors such as (1) physical characteristics of the structure, (2) dynamic
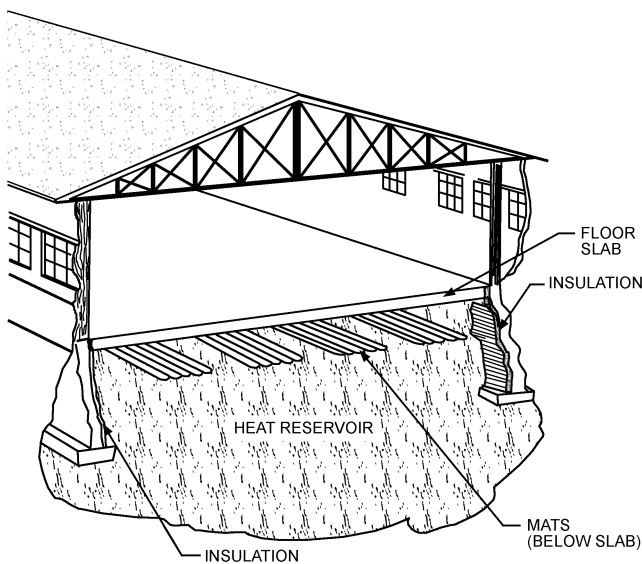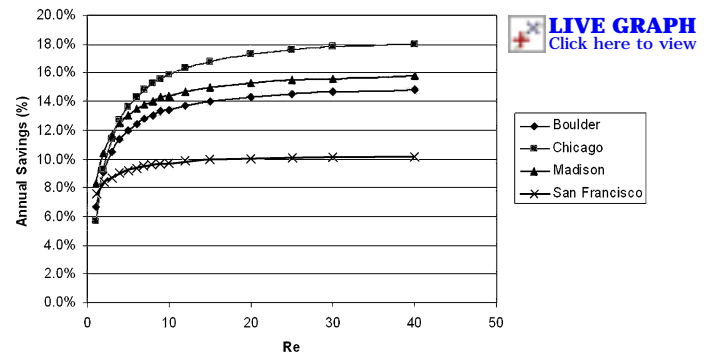
Fig. 16 Annual Energy Cost Savings from Precooling, Relative to Conventional Controls, as Function of R_e
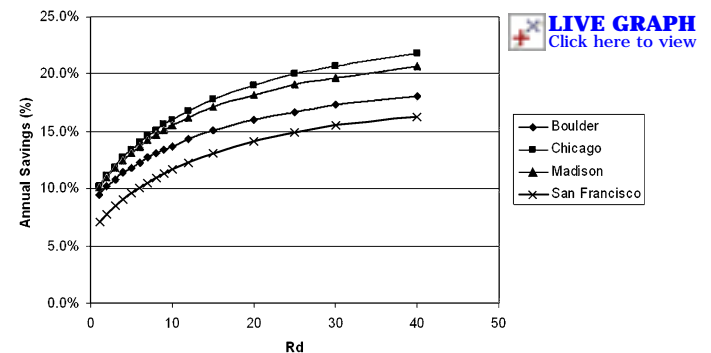
Fig. 17 Annual Energy Cost Savings from Precooling, Relative to Conventional Controls, as Function of R_d

Fig. 15 Underfloor Heat Storage

nature of the building loads, (3) coupling between the building mass and zone air (Akbari et al. 1986), and (4) strategies for charging and discharging the stored thermal energy. Some buildings, such as frame buildings with no interior mass, are inappropriate for this type of thermal storage. Many other physical characteristics of a building or an individual zone, such as carpeting, ceiling plenums, interior partitions, and furnishings, affect the quantity of thermal storage and the coupling of the building mass with zone air.

Incidental Thermal Mass Effects. A greater amount of thermal energy is required to bring a room in a heavyweight building to a suitable condition before occupancy than for a similarly sized light-weight building. Therefore, the system must either start conditioning the spaces earlier or operate at a greater-capacity output. During the occupied period, a heavyweight building requires a smaller output, because a larger proportion of heat gains or losses is absorbed by the thermal mass.

Advantage can be taken of these effects if low-cost electrical energy is available during the night and the air-conditioning system can be operated during this period to precool the building mass. This can reduce both the peak electric demand and total energy required during the following day (Braun 1990; Morgan and Krarti 2006), but it may not always be energy efficient.

Intentional Thermal Mass Effects. To make best use of thermal mass, the building should be designed with this objective in mind. Intentional use of the thermal mass can be either passive or active. Passive solar heating is a common application that uses the thermal mass of the building to provide warmth outside the sunlit period. This effect is discussed in further detail in Chapter 33. Passive cooling applies the same principles to limit the temperature rise during the day. In some climate zones, the spaces can be naturally ventilated overnight to remove surplus heat from the building mass. This technique works well in moderate climates with a wide diurnal temperature swing and low relative humidity, but it is limited by the lack of control over the cooling rate.

Active systems overcome some of the disadvantages of passive systems by using (1) mechanical power to help heat and cool the building and (2) appropriate controls to limit output during the release or discharge period.

Storage Charging and Discharging

The building mass can be charged (cooled or warmed) either indirectly or directly. Indirect charging is usually accomplished by heating or cooling either the bounded space or an adjacent void. Almost all passive and some active cooling systems are charged by cooling the space overnight (Arnold 1978). Most indirect active systems charge by ventilating the void beneath a raised floor (Crane 1991; Herman 1980). Where this is an intermediate floor, cooling can be radiated into the space below and convected from the floor void the following day. By varying the rate of ventilation through the floor void, the rate of storage discharge can be controlled. Proprietary floor slabs commonly have hollow cores (Anderson et al. 1979; Willis and Wilkins 1993). The cores are continuous, but when used for thermal storage, they are plugged at each end, and holes are drilled to provide the proper airflow. Charging is carried out by circulating cool or warm air through the hollow cores and exhausting it into the room. Fan discharge air can be controlled by a ducted switching unit that directs air through the slab or directly into the space.

A directly charged slab, used commonly for heating and occasionally for cooling, can be constructed with an embedded hydronic coil. Refer to Chapter 6 in the 2004 *ASHRAE Handbook—HVAC Systems and Equipment* for design details. The temperature of the slab is only cycled 3 to 5°F to either side of the daily mean temperature of the slab. Consequently, the technique can use very-low-grade free cooling (approximately 66°F) (Meierhans 1993) or low-grade heat (approximately 82°F) rejected from condensers. In cooling applications the slab is used as a cool radiant ceiling, and for

warming it is usually a heated floor. Little control is necessary because of the small temperature differences and the high heat storage capacity of the slab.

The amount of heat stored in a slab equals the product of mass, specific heat, and temperature rise. The amount of heat available to the space depends on the rate at which heat can be transferred between the slab and the surrounding spaces. The combined radiant/convective heat transfer coefficient is generally quite low; for example, a typical value for room surfaces is 1.4 Btu/h·ft^2·°F.

Design Considerations

Many factors must be considered when an energy source is time dependent. The minimum temperature occurs just before dawn, which may be at the end of the off-peak period, and the optimum charge period may run into the working day. Beginning the charge earlier may be less expensive but also less energy efficient. In addition, energy stored in the building mass is neither isolated nor insulated, so some energy is lost during charging, and the amount of available free energy (cooler outside air when suitable and available) varies and must be balanced against the energy cost of mechanical power. As a result, there is a tradeoff that varies with time between the amount of free energy that can be stored and the power necessary for charging.

The cooling capacity is, in effect, embedded in the building thermal mass; therefore conventional techniques of assessing the peak load cannot be used. Detailed weather records that show peaks over several 3 to 5 day periods, as well as data on either side of the peaks, should be examined to ensure that (1) the temperature at which the building fabric is assumed to be before the peak period is realistic and (2) the consequences of running with exhausted storage after the peak period are considered. This level of analysis can only be carried out effectively using a dynamic simulation program. Experience has shown that these programs should be used with a degree of caution, and the results should be compared with both experience and intuition.

Factors Favoring Thermal Storage

Thermal storage is particularly attractive in situations where one or more of the following conditions are present:

New Investment in Chiller Plant Required. A key factor favoring thermal storage is whether the owner must invest in a conventional chiller system (new or an expansion) if thermal storage is not used. This typically occurs during (1) new construction, (2) facility expansions, and (3) chiller plant expansions and rehabs.

Thermal storage systems generally require smaller refrigerating equipment than nonstorage systems. Air and water distribution equipment may also be smaller, and electrical primary power distribution requirements may be significantly smaller. In many situations, the reduced cost of this equipment can partially, completely, or more than completely offset the cost of the thermal storage equipment (Andrepont 2005; Andrepont and Rice 2002), and the operating cost benefits of thermal storage are thereby achieved at a lower cost. For an existing plant that is to be expanded, the additional loads can often be met by thermal storage at a lower cost than adding new chillers, pumps, cooling towers, and mechanical room space (Andrepont and Kohlenberg 2005).

Peak Load Higher Than Average Load. Because thermal storage systems are generally sized for the average expected load, they can provide significant equipment size reductions and cost savings for applications with high peak load spikes. Buildings such as churches, entertainment and sports facilities, convention centers, and some industrial processes can achieve particular benefits. In addition, most commercial and educational facilities also have load profiles conducive to thermal storage.

Favorable Utility Rates. Utility rates often include on-peak and off-peak schedules. On-peak demand and energy charges are higher than off-peak charges, reflecting the utility company's increased

cost of meeting high daytime power demands. Some rate schedules include a ratcheted demand charge, which normally bases the demand charge for the current month on the highest demand incurred during any of the previous 12 months. High demand charges and ratcheted rates, as well as large differences between on-peak and off-peak energy charges, favor the use of cool storage to reduce operating costs.

Real-time pricing structures, which substitute time-varying energy charges for the more prevalent demand/energy structure, are becoming more common. Real-time pricing structures that feature high daily price spikes of relatively short duration also favor the use of cool storage.

Owners with cool storage systems can sometimes negotiate more favorable electric rates from their energy suppliers based on their capability to reduce their electric load during certain peak electric demand periods.

In areas where the electricity supply is limited, thermal storage is attractive because it allows a building to be conditioned with a much lower electrical peak demand.

Back-Up or Redundant Cooling Desirable. A properly designed thermal storage system can easily be maintained over long periods and discharged quickly when needed.

Thermal storage can provide cooling if the emergency back-up power supply is sized to run just the pumps. Thermal storage can also reduce the size of a full back-up power supply, because of the reduced power of the thermal storage system compared to a traditional full chiller system.

Thermal storage in combination with conventional chiller(s) can provide a larger portion of the daytime cooling required if one chiller goes down. For example, in a typical traditional system with two chillers, each is sized for 50% of the load. In a thermal storage system with two chillers, with each sized for 25% of the peak load, and thermal storage, if one chiller breaks down there will be 25% capacity from the chiller plus 50% capacity from the thermal storage, for a total of 75% of full capacity. If the chiller remains out of service for an extended period of time, the one chiller can typically recharge more than half the thermal storage so the capacity available is always above 50%. In the nonstorage system, there would only be 50% capacity available.

Cold-Air Distribution Desirable. Cold-air distribution, with supply air temperatures below the traditional 55°F, allows smaller fans and ducts to cool the spaces, and the system can maintain a lower space humidity (Kirkpatrick and Elleson 1997). Thermal storage and cold-air distribution should be considered for applications that have limited space for fans and ducts, require increased capacity from existing fans and ducts, or require (or could benefit from) lower space relative humidity.

Storage for Fire Protection Beneficial. Chilled-water thermal storage can be configured to provide a fire-protection water supply at a much lower cost than installing separate systems by equipping the storage tank with fire nozzles (Holness 1992; Hussain and Peters 1992; Meckler 1992).

Environmental Benefits Sought. Thermal storage can provide environmental benefits related to reduced source energy use, decreased refrigerant charge, and improved efficiency of the energy supply.

Thermal storage systems can operate with lower energy use than comparable nonstorage systems for several reasons. Cool storage systems benefit from operating chillers at lower condensing temperatures during nighttime operation. Thermal storage provides the opportunity to run a heating or cooling plant at its peak efficiency during 100% of its operating period, for a much higher dynamic operating efficiency. Because equipment in a nonstorage system has to follow the building load profile, the majority of its operation is at part-load conditions, which, for most systems, is much less efficient. Thermal energy storage also enables the practical incorporation of other high-efficiency technologies such as cold-air

distribution and nighttime heat recovery. Several facilities have demonstrated site energy reductions with the application of thermal energy storage (Bahnfleth and Joyce 1994; Fiorino 1994; Goss et al. 1996).

Most thermal energy storage systems reduce the size of refrigerating equipment needed. Reduced refrigeration equipment size means less on-site refrigerant usage and lower probability of environmental problems caused by a leak.

In addition to the potential reduction in energy use at the building site, thermal storage systems can reduce source energy use and emissions at the generating plant. Typically, the base-load power generating equipment that generates most off-peak electricity is more efficient and less polluting than the peaking plants that are used to meet high daytime demand. Transmission and distribution losses are also lower when the supply networks are more lightly loaded and when ambient temperatures are lower. Because thermal storage systems shift the site energy use from on-peak to off-peak periods, the total source energy and power plant emissions required to deliver cooling to the facility will be lower (Gansler et al. 2001; Reindl et al. 1995). In addition, by reducing peak demand, thermal storage helps prevent or delay the need to construct additional power generation and transmission equipment.

Thermal storage also has beneficial effects on combined heat and power systems by matching the thermal and electric load profiles.

The U.S. Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED) rating system seeks to encourage sustainable design. The system awards points for various sustainable design features, including reductions in annual energy cost compared to a standard reference building. Thermal storage is a good way for a building to reduce energy cost and comply with the LEED rating system, and has been used in many buildings that have received LEED certification.

Factors Discouraging Thermal Storage

Thermal storage may be difficult to justify economically if

- Cooling load profile is flat, with very little difference between the peak and average loads
- Available utility rates do not differ between night and day electrical costs
- Space is not available indoors or outdoors for thermal storage tank(s)

Note that even when one or more of these conditions are true, thermal storage may still be justified by the factors favoring thermal storage. In addition, thermal storage should be integrated into the initial cooling system design for it to achieve the greatest economic benefit for the owner and operator.

Typical Applications

Few applications are not suited to thermal storage. Particularly well suited to thermal storage are sports and entertainment facilities, convention centers, churches, airports, schools and universities, military bases, and office buildings, because they have widely varying loads. The average cooling load for these buildings is much lower than the peak load. In addition, using high temperature differentials for chilled-water and air distribution can significantly reduce construction costs, and decrease utility bills.

Health care facilities, data centers, and hotels having loads with only a slight variation between day and night may also be suited for thermal storage. Normally, the thermal storage should be sized to handle the variation in load, not the total load. Thermal storage can provide a steady supply temperature when rapid changes in operating or meeting room temperatures are required. High temperature differentials for chilled-water and air distribution can significantly reduce construction costs, and the lower electrical demand can also reduce the size of emergency back-up generators.

District Cooling Systems. District cooling systems benefit from thermal storage in several ways. The cost of the distribution system in district cooling applications is a large percentage of the total system cost. As a result, when higher temperature differentials available from thermal storage media are used, life-cycle costs can be lower by using smaller pipes, valves, pumps, heat exchangers, motors, starters, etc. Energy costs of chilled-water distribution are thereby reduced. Thermal storage can provide a steady supply temperature when rapid changes in load occur. The lower electrical demand may reduce the size of emergency back-up generators.

Furthermore, thermal storage may be used to increase the available cooling capacity of an existing chilled-water distribution system by providing cooler supply water. This modification has little effect on the distribution system itself (i.e., pumping and piping) during peak load, because the existing system flow rates and pressure drops do not change. During off-peak cooling load conditions, pumping energy costs can be greatly reduced, because the flow rate can be reduced proportionate to the reduced load.

Most storage tanks are open, so attention should be given to system hydraulics when connecting several plants to a common distribution network where storage tank water levels are at different elevations. Chapter 11 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment* has additional information on district systems and related topics.

Industrial/Process Cooling. Industrial refrigeration and process cooling typically require lower temperatures than environmental air conditioning. Applications such as vegetable hydrocooling, milk cooling, carcass spray-cooling, and storage room dehumidification can use cold water from an ice storage system. Lower temperatures for freezing food, storing frozen food, and so forth can be obtained by using a low-temperature sensible energy storage fluid, a low-temperature hydrated salt PCM charged and discharged by a secondary coolant, or a nonaqueous PCM such as CO_2.

Some of the advantages of cool storage may be particularly important for industrial refrigeration and process cooling applications. Cool storage can provide a steady supply temperature regardless of large, rapid changes in cooling load or return temperature. Charging equipment and discharging pumps can be placed on separate electrical service to economically provide cooling during a power failure or to take advantage of low, interruptible electric rates. Storage tanks can also be oversized to provide water for emergency cooling or fire fighting. Cooling can be extracted very quickly from a thermal storage system to satisfy a very large load and then be recharged slowly, using a small charging system. System design may be simplified when the load profile is determined by production scheduling rather than occupancy and outdoor temperatures.

Combustion Turbine Inlet Air Cooling. Cool storage can increase the capacity and efficiency of combustion turbines by precooling the inlet air. Oil- or gas-fired combustion turbines typically generate full rated output at an inlet air temperature of 59°F, and above rated output below 59°F. At higher inlet air temperatures, the density and thus the mass flow of air is reduced, decreasing the shaft power and fuel efficiency. Capacity and efficiency can be increased by precooling inlet combustion air with chilled-water coils or direct-contact cooling. The optimum inlet air temperature is typically in the range of 40 to 50°F, depending on the turbine model.

On a 100°F summer day, a combustion turbine driving a generator may lose up to 25% of its rated output. This drop in generator output occurs at the most inopportune time, when an electrical utility or industrial user is most in need of the additional electrical output available from combined cycle or peaking turbines. This lost capacity can be regained if the inlet air is artificially cooled (Andrepont 1994; Ebeling et al. 1994; MacCracken 1994; Mackie 1994). Cool storage systems using chilled water or ice are well suited to this application because the cooling is generated and stored during off-peak periods, when demand for the generator output is lower, and the maximum net increase in generator capacity is obtained by turning off the refrigeration compressor during peak demand periods, providing the added generator capacity at the time it is needed most (Andrepont 2001; Cross et al. 1995; Liebendorfer and Andrepont 2005). Some parasitic power is required to operate water pumps to use the stored cooling energy.

Although instantaneous cooling can also be used for inlet air precooling, this refrigeration equipment often uses 25 to 50% of the increased turbine power output. It is especially taxing because the maximum need occurs during times of highest cost for energy and lowest output of the direct cooling compressor, because of the higher ambient temperature. Cool storage systems can meet all or part of the load requirements for inlet air precooling. Evaporative coolers are also a simple and well-established technology for inlet air precooling, but they cannot deliver the low air temperatures available from refrigeration systems. Additional information can be found in the *Design Guide for Combustion Turbine Inlet Air Cooling Systems* (Stewart 1999).

Mission-Critical Operations. Thermal storage systems can be used for emergency back-up cooling during unplanned downtime of the chillers that serve mission-critical operations such as data processing centers. Such operations cannot tolerate even short periods of cooling interruptions. If a chiller serving one of these areas unexpectedly goes off-line, it will take at least 20 min to restart the chiller, during which time some kind of back-up cooling is required. Providing emergency back-up cooling with cool storage is typically more economical to install and operate than a redundant air-conditioning system.

SIZING COOL STORAGE SYSTEMS

A first step in sizing a cool storage system is to determine the amount of the design load to be met from storage. Proper sizing requires calculating a design load profile and determining the required chiller and storage capacity to meet the load profile.

Sizing Strategies

Cool storage systems can be sized for full or partial storage operation on the design day. A full storage, or load-shifting system, meets the entire design day on-peak cooling load from storage. A partial storage system meets a portion of the design day on-peak cooling load from storage, with the remainder of the load met by operating the chilling equipment. A load-leveling design is a partial storage approach that minimizes equipment size and storage capacity. The system operates with refrigeration equipment running at full capacity for 24 h to meet the design load profile. When the load is less than the chiller output, the excess cooling is stored. When the load exceeds the chiller capacity, the additional requirement is discharged from storage.

Calculating Load Profiles

An accurate calculation of the design load profile is important to the success of a cool storage design, for several reasons, such as the following:

- To determine the amount of storage capacity required, the total integrated cooling load must be known.
- To ensure that the storage capacity is available when it is needed, the timing of the loads must be known.
- To ensure that cool storage suppliers provide equipment with the appropriate performance, the load profile must be specified.

Knowledge of the cooling load is required for each hour of the storage cycle, which, for most systems, is a 24 h design day. A cool storage system based on an erroneous load calculation may be undersized and unable to meet the full load, or it may be oversized and unnecessarily expensive and inefficient. Note, however, that in some cases designers may intentionally specify excess capacity to provide for future load increases.

The shape of the load profile also affects the performance characteristics of storage systems. For example, many cool storage systems respond differently to a constant load than to a load that increases to a peak and then decreases to a lower level. Therefore, it is important to accurately calculate the load for each hour of the storage and discharge cycles to allow designing to the proper total and instantaneous capacities.

Calculating loads for storage systems is similar to that for nonstorage designs, except that all heat gains for the entire design day, on an hourly basis, must be considered.

Select design temperatures with care, based on the allowable number of hours that the load may exceed the system capacity. Note that system performance is dependent on the sequence of weather conditions as well as the peak daily condition. Colliver et al. (1998) developed design weather profiles for locations across North America, with design weather conditions for one, three, five, and seven consecutive days.

Establish accurate schedules of occupancy, lighting, and equipment use. For example, if equipment, such as computers, operates continuously, heat gains during unoccupied periods are significant. The schedules should account for any changes to occur in the foreseeable future.

Include all sources of heat in the conditioned space. Nearly all electric input to the building, as well as external heat gains from conduction and solar radiation, will eventually become a load on the cool storage system. Include reheat load when reheat is to be used and include heat gains from the surroundings to the storage tank. Gatley and Riticher (1985) present detailed lists of often-overlooked heat sources that can significantly affect the load profile.

Consider any pull-down loads, which accumulate when systems are shut down during unoccupied periods, and must be met during the first minutes or hours of system operation.

Use the expected relative humidity in the building to calculate latent heat gains from infiltration, especially if supply air temperatures are to be reduced.

Note that there are two types of design days for cool storage applications: the day with the maximum 1 h cooling load for the year, and the day with the maximum integrated load over a 24 h period. In some buildings, these two types of peaks will not occur on the same day. Systems must be sized to provide sufficient cooling capacity on the day with the highest integrated cooling load as well as the day with the highest hourly load.

Recognize that the calculated building load does not represent the chilled-water load on the central plant. To obtain the load profile for the cooling plant, the designer must consider the operation of the air and water distribution systems that are used to meet the loads. This analysis should include

- Control sequences for chilled water coils and space temperatures, including set points and throttling ranges
- Fan and duct heat gains
- Pump and piping heat gains
- Heat gains to the storage system from external conduction to the storage tank

Load calculations for cool storage systems are discussed further in the *Design Guide for Cool Thermal Storage* (Dorgan and Elleson 1993). General air-conditioning cooling load calculations are discussed in detail in Chapter 30 of the 2005 ASHRAE *Handbook—Fundamentals*.

When cool storage is to be installed in an existing facility, determining loads by direct measurement may be preferable to estimating the loads. Load data may be available from logs collected by the building automation system, from chiller logs maintained by operating personnel, or from on-site measurements made over a period of design or near-design weather conditions. Field measurements should be verified by comparison with reference instruments of known accuracy, energy balance calculations, or some other external

verification. Note that, if the load on an existing system exceeds the capacity of the existing equipment, measured loads will be limited by the equipment capacity and may not reflect the actual loads.

Sizing Equipment

Quick sizing formulas are available to estimate the chiller and storage capacities necessary to meet a given load profile. However, accurate evaluation of chiller performance and storage at the appropriate conditions for each hour of the design cooling cycle is required for proper sizing of equipment.

Unlike most air-conditioning and refrigeration equipment, cool storage devices have no sustained, steady-state operating condition at which equipment performance can be characterized using standard parameters. The *usable* storage capacity of a cool storage device may vary appreciably depending on the application (ARI *Guideline* T).

Usable capacity depends on the load profile and temperature requirements that the cool storage equipment must meet. Net usable capacity is typically not equal to, and in fact is nearly always less than, the nominal capacity. The designer must carry out an hourly analysis to determine the nominal storage capacity and discharging capacity required to meet a given load profile. Hourly analysis is also necessary to specify the thermal performance that cool storage equipment must provide.

Specifications for cool storage equipment must include the operating profile that the equipment is required to meet. (Omitting the operating profile from the cool storage specification is comparable to omitting the design chilled-water and condenser water temperatures from a chiller specification.) The design team must prepare an hourly operating profile to select the appropriate chiller and storage capacities to meet the load. The operating profile defines the system operating conditions each hour of the complete storage cycle. Most cool storage systems are designed for a one-day storage cycle, and the operating profile includes data for a 24 h period.

In addition to determining capacity requirements, designers use the hourly operating profile to

- Develop control sequences
- Define performance requirements that suppliers of storage equipment must meet and against which commissioners must validate actual performance
- Determine requirements for components such as pumps and heat exchangers
- Evaluate system performance after it is installed

The operating profile must include the following information for each hour of the storage cycle:

- Ambient dry- and wet-bulb temperatures
- Total system load
- Load met by chiller(s)
- Load met by storage equipment
- Fluid temperature(s) entering chiller(s)
- Fluid temperature(s) leaving chiller(s)
- Fluid flow rate to chiller(s)
- Fluid temperature(s) entering storage
- Fluid temperature(s) leaving storage
- Fluid flow rate to storage (charging mode)
- Fluid flow rate leaving storage (discharging mode)
- Fluid pressure drop through storage, chiller and piping system
- Total capacity (ton-hours) of usable stored cooling
- Maximum cooling capacity or electric demand for chilling equipment

The hourly operating profile should be developed using manufacturers' performance data for specific chiller and storage selections. Typically, designers must iterate between chiller data and storage data to determine the balance between the components. For example, the storage performance characteristics determine the

temperatures required to charge storage with a given chiller capacity. Chiller capacity varies with fluid flow rate and temperature entering the evaporator, and with condensing temperature.

The capacity and performance of existing chillers and cooling towers may not be equal to the original ratings, because of fouling or other deterioration. Performance ratings also need to be adjusted to account for the new anticipated operating conditions. Capacity of the existing chillers should be verified by test before completing the sizing of the storage system.

ARI *Guideline* T defines the minimum information to be provided by prospective users when specifying performance requirements for cool storage equipment, and the minimum information to be provided by suppliers about their equipment's thermal performance. The hourly operating profile as described previously includes user-specified data requirements from *Guideline* T, as well as additional information useful for design.

The project specification should require that submittals for cool storage equipment provide all supplier-specified information required by *Guideline* T. The project specification should also require that the equipment be guaranteed to perform as represented by the submittal data when tested according to a specified procedure. Test methods are discussed in ASHRAE *Standards* 94.2 and 94.3.

The capacity of chilling equipment is an important aspect of sizing a cool storage system. ARI *Standard* 550 allows actual capacities to deviate by approximately ±5% from the manufacturer's ratings. A 5% shortfall in chiller capacity, accumulated over one or more storage cycles, can result in a significant shortage of cooling capacity, which may make it impossible to meet the design cooling loads.

Designers may wish to include a requirement for zero negative capacity tolerance in chiller specifications. Such a requirement should also include provisions for factory testing and certification of the actual chiller's capacity. This may be a consultant- and/or customer-witnessed test. Some designers may elect to include a safety factor of 5 to 10% in the chiller capacity specification. This can be accomplished, for example, by specifying a chiller capable of cooling 105% of the design flow rate at the design temperatures (Dorgan and Elleson 1993).

Judicious use of safety factors is good engineering practice. However, the economics of cool storage are particularly sensitive to misapplication of safety factors. Safety factors should not be used as a substitute for sound engineering principles. The most successful systems are designed with modest safety factors for chiller and storage capacity.

Successful systems are also designed with flexibility to change operating strategies if operating requirements change or if loads increase. In cases with a high probability of increased future loads, designs should include provisions for adding capacity. Operating strategies should, as a minimum, be designed to ensure that excess capacity is used to full advantage, if actual loads are lower than projected. This further reduces operating costs.

APPLICATION OF THERMAL STORAGE SYSTEMS

Chilled-Water Storage Systems

Sensible storage may be applied to any cooling load within its application temperature range. Stratified chilled-water storage systems have been successfully applied in hospitals, schools, industrial facilities, campus and district cooling systems, power generation (combustion turbine inlet air cooling), emergency cooling systems, and others. Sensible storage tends to be the most competitive in large applications (above 3000 ton-hours or millions of gallons of storage medium) because of the low cost per ton-hour of large storage volumes. However, smaller systems are installed occasionally for a variety of reasons. For example, emergency cooling systems that may be required to discharge for only 10 or 20 min may be quite

small relative to typical load-shifting systems. Various thermal storage project delivery methods are possible. Numerous manufacturers produce turnkey storage tanks, and they may team with engineering and construction firms in a design/build relationship. At the other extreme, many systems have been designed successfully by mechanical engineering firms using generic water storage tanks, possibly with the assistance of a specialty consultant to design diffusers and advise on interface design and, possibly, the controls. It is particularly important that the storage design be such that the storage system will be properly integrated with the existing system, so the storage system designer must be expert in chilled-water system design generally.

Sensible storage vessels can be connected to chilled-water systems in a variety of ways. One common approach is to associate the storage system with the chilled-water plant so it functions as an alternative source of capacity but has no effect on distribution of flow to end users. Sensible storage can also be located remotely from the chilled-water plant, in which case it functions like a satellite plant. This approach has been used in systems that were experiencing distribution system capacity limitations (Andrepont and Kohlenberg 2005; Borer and Schwartz 2005). Storage can be charged when loads are low, and used to backfeed the distribution system during peak periods. Examples of several Australian systems with satellite storage are described by Bahnfleth et al. (2003b).

A typical inside-the-plant connection scheme for a stratified sensible storage system serving a primary/secondary chilled-water system is shown in Figure 18. As indicated by flow arrows, the direction of flow between the storage tank and the system must reverse between the charge and discharge modes. The storage vessel is connected to the system by a transfer pumping interface, which controls the direction of flow between the tank and the system and accommodates pressure differences between the system and the tank. This is necessary in stratified tanks (typically open to the atmosphere) only when the tank water level is below the highest point in the chilled-water system. Under such conditions, an interface is needed to exchange thermal energy with the system while preventing the elevated system water from draining into the tank and overflowing.

The transfer pumping interface in Figure 18 may have several configurations, the two most common of which are shown in Figures 19 to 22. These figures are schematic. They do not show pump trim items such as check valves and strainers. One pump is shown, but multiple pumps in parallel are used in many systems. Likewise, parallel control valves may be specified in some systems to provide the required rangeability.

Figure 19 shows a direct interface, which allows water to flow between the tank and the system while maintaining tank and system pressure levels by using modulating pressure-sustaining valves. The example shown has four two-position valves and two pressure-sustaining valves. It is configured so the pump always pumps out of
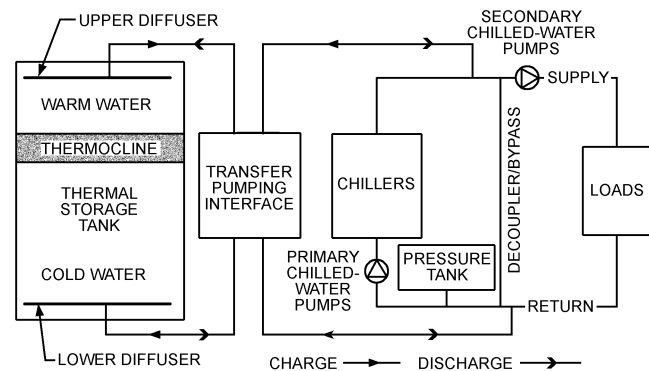
Fig. 18   Typical Sensible Storage Connection Scheme
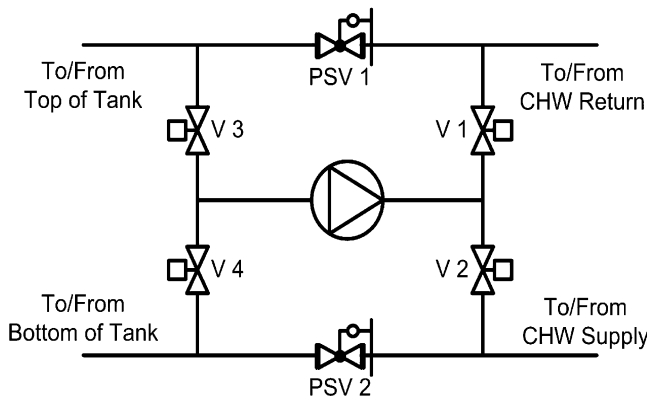
Fig. 19   **Direct Transfer Pumping Interface**
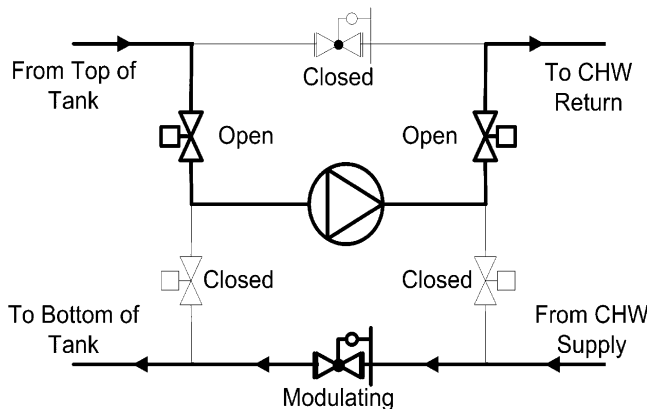
Fig. 20   **Charge Mode Status of Direct Transfer Pumping Interface**

Fig. 21   **Indirect Transfer Pumping Interface**

Fig. 22   **Charge Mode Status of Indirect Transfer Pumping Interface**

the tank into the system (i.e., from the lower-pressure zone to the higher-pressure zone). Figure 20 illustrates valve status and flow paths for charge mode. One pair of two-position valves is open and the other pair is closed, and one pressure-sustaining valve modulates and the other is closed. The status of all valves is reversed during discharge mode.

If the water level in the storage tank is at or above the water level in the tallest building or highest air handler or piping run, pressure-sustaining valves are unnecessary. In this case, the only valves required would be to change flow direction when the system is switched from the charge mode to the discharge mode and vice versa. In some cases (see Figure 23), no valves are needed to change the direction of flow.

Figure 21 is an example of an indirect interface that connects the thermal storage system and the chilled-water system through a heat exchanger, which is typically a plate-and-frame heat exchanger with a 2 to 3°F maximum approach temperature. Figure 22 illustrates valve status and flow paths for charge mode. The advantage of this approach over the direct interface is that it eliminates the pressure control problem, and may save pumping energy if there is a large static pressure difference between the tank and the system. However, the added installation and energy cost of this scheme is significant, because of the number of additional components and unavoidable loss of storage capacity caused by the temperature differences (4 to 6°F) across the heat exchanger during charging and discharging. This loss of differential temperature causes a major penalty in pumping energy consumption.

For example, suppose that the chilled-water system in Figure 18 has a supply (and charging) temperature of 40°F and a return temperature of 60°F. If the heat exchanger in an indirect interface
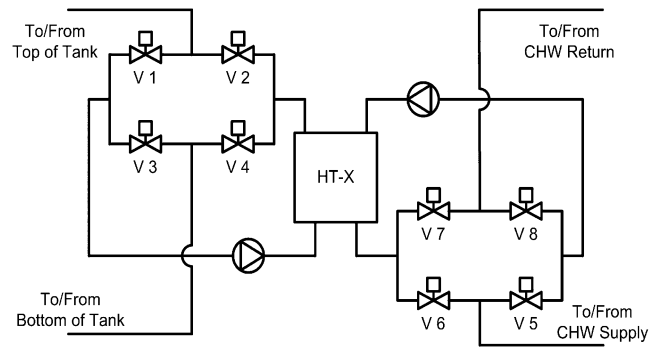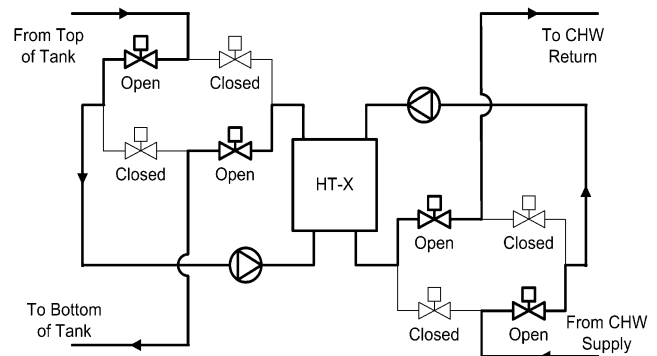
has a 2°F approach, the temperature of water in the charged tank will be 42°F and after complete discharge it will be 58°F. Consequently, the maximum temperature difference to which the storage medium is subjected is 16°F, rather than the 20°F that could be achieved with a direct interface. To have the same capacity as a direct interface system, the tank of the indirect interface system needs to be 25% larger.

Bahnfleth and Kirchner (1999) performed a parametric study of transfer pumping interface economics for direct and indirect interfaces as well as direct interfaces with hydraulic energy recovery. Considering the increased cost of the storage tank to achieve equal storage capacity when an indirect interface is used, this study concluded that, until static pressure differential reaches several hundred feet of water, the life-cycle cost of a direct interface is much more acceptable than for an indirect interface system.

An alternative to the centralized indirect interface shown in Figures 18 and 21 is to isolate loads that are at higher elevation than the tank water level. This may result in lower system cost than a central heat exchanger, and significantly lower pumping energy consumption than a direct interface system. An analysis must be made to determine the total cost and energy consumption of the distributed pump/pressure-sustaining valve approach relative to centrally located valves at the storage tank to ensure that the proper scheme is being specified.

When it is possible to design the thermal storage tank surface to be the high water level in the system, it can function as the expansion tank and possibly provide a much simpler system design. One particularly attractive arrangement is to use the thermal storage tank as the decoupler in a primary/secondary system, as shown in Figure 23. In this system, if the flow demanded by the secondary pump exceeds the flow provided by the primary pump serving the chiller, the difference is withdrawn from the bottom of the tank and replaced by return water at the top. During charging, any surplus flow available from the chiller after the system load is met enters the

bottom of the tank, displacing warm water, which flows from the top of the tank to the chiller.

Figure 23 also represents a possible configuration for a stratified emergency cooling system of the type used in some data centers and other critical loads to cover transitions to emergency systems during an equipment failure. These systems may discharge at a very high rate for a period of only a few minutes. A piping and control configuration that allows stored capacity to be available instantly, without any valve repositioning, is required.

Ice (and PCM) Storage Systems

Partial storage applications present the greatest challenge in allocating the relative contributions of chiller and storage to the cooling load. The goal is to minimize energy cost while preventing premature exhaustion of the storage capacity. Storage devices have a finite total capacity in ton-hours and an instantaneous capacity (tons) that may vary with storage inventory and coolant temperature. Ice storage systems that use secondary coolants incorporate most of the essential design elements, and the following discussion assumes this type of storage system. Note that, even on the design day, there are hours that are less than peak load. A conventional-system chiller would unload during these hours, but partial storage sizing often takes advantage of the fact that the chiller can be fully loaded throughout the design day, minimizing the investment in equipment and maximizing the efficiency of chiller operation.

On the design day, the operating logic is usually predetermined and obvious. The challenge in maximizing energy and demand savings usually occurs on days with reduced load, which, of course, comprises most of the operating hours. Control schemes can be as simple or as complex as desired, consistent with the utility rate; building load patterns; and the training, experience, and commitment of the system operators. Very effective control schemes have been as straightforward as hot day/mild day/cool day. The chiller is fully loaded on a hot day, half-loaded on a mild day, and off on a cool day. An increased level of complexity might attempt to limit demand for each billing period. There is a minimum chiller demand that can be predicted for any billing period, either by analysis of cooling loads, from experience, or established by a demand ratchet from a previous month

Because there is no avoidable demand penalty (kilowatts) for chiller operation up to this level, the cost of energy (kilowatt-hours) becomes the dominant influence when lower-load days are addressed. If there is a significant difference in on-peak and off-peak rates, further reduction in the hours of on-peak chiller operation is

warranted, if practical. If the rates are approximately equal, chiller operation up to this preestablished limit carries no penalty. In either case, demand savings are maximized. Even more complex methods are available that track storage inventory, cooling load, outdoor conditions, etc., and then modulate chiller loading to maximize savings under specific utility rates. In most cases, simple control schemes are very effective and more long-lasting with the operators.

The three-way storage valve (V1 in Figures 24 to 26) responds to two separate system characteristics: (1) the variation in the required contribution from storage as the building load ramps up and down and as the chiller capacity varies, and (2) the storage system's variable performance.

The temperature of coolant exiting the storage device is a function of flow, inlet temperature, and ice inventory. The temperature-modulating valve automatically compensates for all of these effects, in addition to providing isolation of storage when necessary.

Ice Making. Each system depicted in Figures 24 to 26 includes a temperature-blending valve (V1) around the storage module. This valve is simply driven to direct all flow through the storage device during the ice-making period. Termination of ice making may be indicated by an inventory measurement or by the attainment of a specific coolant temperature. The chiller is typically fully loaded for the duration of ice making. Once a full charge is reached, further ice-making operation is prevented until the next scheduled ice-making period.

It is often necessary to serve a cooling load during the charging mode. The ability to efficiently meet small night loads is a major advantage of storage systems. The temperature of coolant circulating in the primary loop during charge mode is below 32°F and considerably lower than that normally delivered to the secondary load loop. Although a separate chiller operating at a higher temperature can be used to meet night loads, an additional three-way valve (V2) and bypass (illustrated in Figures 24 to 26) is often placed in the secondary loop so warm return fluid can temper the coolant delivered to the load from the ice-making primary loop. This is critical when pure water load loops are served through a heat exchanger. If a night load is present after charging is completed, valve V1 can be positioned to bypass storage, and the chiller can be operated at standard daytime temperatures. If no night loads (i.e., during ice-making) are anticipated, this valve and bypass can be eliminated, because all daytime temperature control can be accomplished with the chiller or storage three-way valve.

Series Configuration. A common piping scheme is to place the chiller and storage in series. This arrangement provides several advantages. It does not require a change in flow path during charging when both storage and chiller must be in series. A parallel arrangement usually necessitates a change in flow path as the system cycles between charge and discharge. Simple control mechanisms can be used to vary the contribution of each component to the cooling load. All modes of operation (chiller only, ice only, or any ratio of chiller and ice) are easily implemented. Also, the manufacturer may recommend that flow through the storage equipment be in the same direction for charge and discharge. The series arrangement automatically accomplishes this.

Partial storage systems use on-peak chiller capacities that typically vary from 40 to 70% of the peak load. Because it would be difficult to direct full system flow through the smaller chiller and storage at the common 10 or 12°F temperature range, series systems often use a wider differential Δt in supply and return temperatures. Ranges of 14 to 16°F are fairly common, with up to 20°F occasionally used. Flow rates are consequently lowered to levels compatible with the equipment, and pumping energy can be reduced throughout the system. For the series flow examples, 42°F supply and 58°F return at peak load are assumed.

Series Flow, Chiller Upstream. In the upstream position (Figure 24), the chiller often operates at higher daytime evaporator
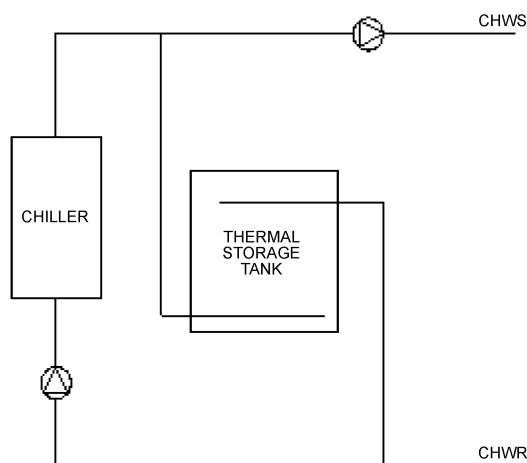
Fig. 23   Primary/Secondary Chilled-Water Plant with Stratified Storage Tank as Decoupler

temperatures than it would have in the conventional system, although there may be a negative effect on total storage capacity.

If the maximum on-peak chiller capacity is half of the on-peak load, the chiller reduces the return temperature by half the design Δ*t*, to 50°F at peak load. However, if the chiller leaving chilled-water temperature (LCWT) is simply set to 50°F, the chiller will unload any time the load is less than peak, as the return temperature decreases. This may shift cooling load to storage that should have been served by the chiller, resulting in premature depletion of storage capacity and the inability to meet the cooling load later in the day. Alternatively, by setting the chiller LCWT at 42°F, the chiller meets all cooling loads up to its full capacity, before any load is imposed on storage. In some cases, this can be the extent of the discharge control logic. In fact, through simple adjustment of the chiller supply water temperature set point or chiller demand limits, cooling load can be shifted between chiller and storage in any desired proportion to best exploit the electric rate in response to daily or seasonal load changes. As the load fluctuates and the related chiller contribution varies, the storage three-way modulating valve automatically directs sufficient flow through the storage system to maintain 42°F coolant delivered to the load.

Series Flow, Chiller Downstream. Reversing the arrangement retains all of the control flexibility, because the storage modulating valve can be used to manage the relative contributions of storage and chiller (Figure 25). Storage capacity is maximized at the expense of some chiller efficiency, which in many cases is minimal. At peak load, the storage blending valve is set to 50°F, and the chiller will be fully loaded as it further reduces the temperature to 42°F. Maintaining this storage temperature set point keeps the chiller fully loaded throughout the day, minimizing use of storage capacity. On cooler days, the storage blended outlet temperature can be reduced. Chiller capacity and electric demand are also reduced. Alternatively, chiller demand limiting can be used and the storage blending valve temperature sensor can be located downstream of the chiller. The storage automatically meets any load in excess of the chiller limit to maintain the desired supply water temperature.

In either the chiller upstream or downstream arrangement, simple temperature control or chiller demand limiting can easily manipulate the cooling loads imposed on either storage or the chiller system.

Parallel Flow. There are times when a parallel flow configuration is preferred, perhaps to address a retrofit application with a fixed-distribution Δ*t*. Chillers in parallel load and unload in response to cooling needs. In storage applications, it is essential that storage is not simultaneously unloaded as the chiller is unloaded.

There are many variations on the parallel flow theme. Referring to the simplified schematic of Figure 26, a two position, three-way valve (V3) at the chiller outlet is included to redirect flow for the charge and discharge modes. This example assumes that the chiller meets 60% of the daytime peak load.

During discharge, in parallel, the same return-temperature fluid enters both the chiller and storage. With no control other than a fixed leaving temperature for both storage and chiller, the contributions of storage and chiller vary in a constant ratio as the return temperature varies. Because even on a design day, the return temperature may be reduced during much of the day, it is apparent that the chiller will unload. If the original selection assumed full capacity from the chiller during all hours, the system would then be undersized.

To avoid this problem, chiller temperature can be allowed to drop to maintain full load, and the storage blending valve sensor can be repositioned to sense the chiller/storage combined flow temperature. Variable-speed pumping of the storage loop is also possible, to maintain a fully loaded chiller at a constant chiller leaving temperature. Storage systems typically have a broad range of acceptable flow rates.

Further complications arise when chillers are demand-limited to optimize utility cost. In a constant-flow chiller loop, the chiller leaving temperature generally rises when the chiller is unloaded, necessitating a drop in storage temperature to compensate. The storage system may not have been selected to operate at the lower temperature. Variable chiller flow can provide a full system Δ*t* at reduced capacity. In any case, it becomes more awkward to optimize load sharing between the chiller and the storage. The best approach is, regardless of system configuration, to calculate flows and temperatures resulting from the proposed control logic at a variety of cooling loads, and ensure that results are consistent with the assumptions made during equipment selection.

A versatile storage design allows the system to shift load between chiller and storage to best exploit the utility rate, thereby optimizing the total utility bill. Accompanying this versatility is the responsibility to ensure that loads are properly shared by chiller and storage under all conditions.
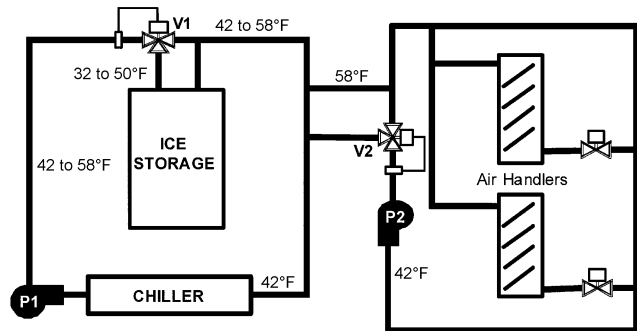
Fig. 25   Series Flow, Chiller Downstream
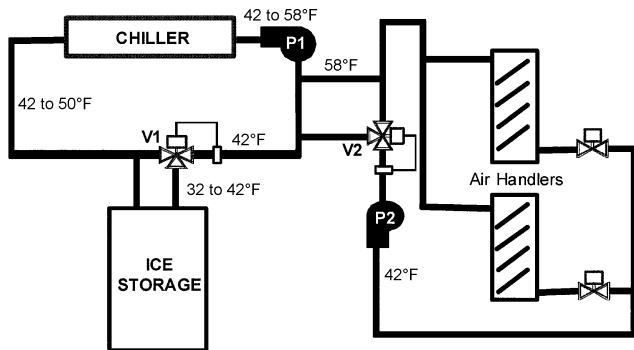
Fig. 24   Series Flow, Chiller Upstream
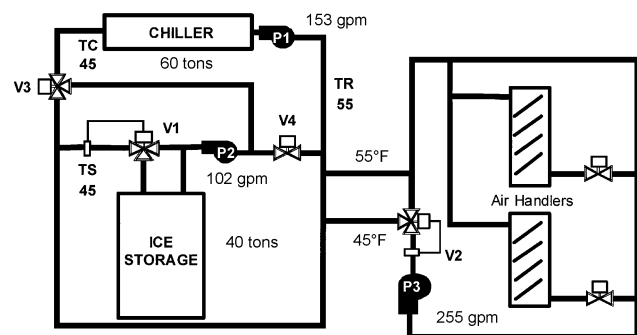
Fig. 26   Parallel Flow for Chiller and Storage

OPERATION AND CONTROL

Thermal storage operation and control is generally more schedule-dependent than that of instantaneous systems. Because thermal storage systems separate the generation of heating and cooling from its use, control of each of these functions must be considered individually. Many thermal storage systems also offer the ability to provide heating or cooling either directly or from storage. This flexibility makes it necessary to define how loads will be met at any time under various scenarios.

ASHRAE Research Project RP-1054 (Dorgan et al. 1999, 2001) developed a framework for describing and characterizing the many methods for controlling thermal storage systems. The methods were defined in terms of the following levels of control:

- Available **operating modes**. A thermal storage operating mode describes which of several possible functions the system is performing at a given time (e.g., charging storage, meeting load directly without storage, meeting load from discharging storage, etc.).
- **Control strategies** used to implement the operating modes. A thermal storage control strategy is the sequence of operating modes implemented under specific conditions of load, weather, season, etc. For example, different control strategies might be implemented on a design day in the summer, a cool day in the summer, and a winter day.
- The **operating strategy** that defines the overall method of control for the thermal storage system to achieve the design intent. The operating strategy provides the logic used to determine when the various operating modes and control strategies are selected. A system designed to minimize on-peak demand uses a different operating strategy than one designed to minimize use of on-peak energy or installed equipment capacity.

The design of a thermal storage system should include a detailed description of the intended operating strategy and its associated control strategies and operating modes. Dorgan et al. (1999, 2001) provides specific recommendations for documenting each of these elements of operation and control. The researchers also recommend that graphical illustrations be used to describe each operating mode and the logic used to select each mode. The documentation should address control for the complete storage cycle under full- and part-load operation, including variations related to seasonal conditions.

The operating mode, control strategy, and operating strategy framework is useful for describing the operation and control of sophisticated thermal storage systems, and for comparing the operation and control of multiple systems. Many systems use a limited number of operating modes and control strategies. For example, a simple storage system may have a single control strategy with just two modes of operation: charging and discharging (meeting load). Although the complete framework is not necessary to describe the control of such a system, it is still important for the designer to recognize and document how a system is intended to be controlled under all conditions.

Design documentation should also include the basic parameters that helped determine the operating strategy, sizing strategy (full or partial storage), the energy cost structure and the general design intent.

Operating Modes

The five most common thermal storage operating modes are described in Table 2. The operating modes used in each individual thermal storage system design vary. Some systems may use fewer modes; for example, the option to meet a building load while charging may not be available for a specific system design, when there is no cooling load during the time the system is being charged. Many systems operate under only two modes of operation: daytime and nighttime.

Table 2 Common Thermal Storage Operating Modes

Operating Mode	Heat Storage	Cool Storage
Charging storage	Operating heating equipment to add heat to storage	Operating cooling equipment to remove heat from storage
Charging storage while meeting loads	Operating heating equipment to add heat to storage *and* meet loads	Operating cooling equipment to remove heat from storage *and* meet loads
Meeting loads from storage only	Discharging (removing heat from) storage to meet loads without operating heating equipment	Discharging (adding heat to) storage to meet loads without operating cooling equipment
Meeting loads from storage and direct equipment operation	Discharging (removing heat from) storage *and* operating heating equipment to meet loads	Discharging (adding heat to) storage *and* operating cooling equipment to meet loads
Meeting loads from direct equipment operation only	Operating heating equipment to meet loads (no fluid flow to or from storage)	Operating cooling equipment to meet loads (no fluid flow to or from storage)

Many systems also include additional operating modes, such as

- Charging cool storage from free cooling (hydronic economizer)
- Charging cool storage while recovering condenser heat
- Charging heat storage with recovered condenser heat
- Discharging at distinct supply temperatures
- Discharging in conjunction with various combinations of equipment

In general, the control system selects the current operating mode based on the time of day and day of the week. Other factors that may be considered in this selection include outdoor air temperature, current system load, total facility utility demand at the billing meter, and amount of storage available compared to the storage system capacity. The logic for mode selection is defined as part of the operating strategy.

In some cases, particularly for large cool storage systems with multiple chillers and multiple loads, different operating modes or control strategies may be applied to different parts of the system at one time. For example, one chiller may operate in charging-only mode, while another chiller may operate only to meet a building load.

An operating mode is defined by its control sequence, or sequence of operation. The specified control sequence defines the specifics of what equipment is to be operated, the values of the control system set points, the function of each control valve and other control device, and any other function necessary to achieve the design intent for that operating mode. These all result in a description of individual control loops and their responses to changes in loads or other variables.

Charging Storage with No Load. Control sequences for the storage charging-only mode are generally easily defined. Typically, the generation equipment (e.g., chillers or boilers) operates at full capacity with a constant supply temperature set point and constant flow through the storage system. Charging begins at a specified time and continues until the storage is considered fully charged or the period available for charging has ended. Under this scenario, all equipment designated as being available for charging is operated for storage purposes.

Charging Storage While Meeting the Load. This mode is more complex than the charging-only mode, but is necessary in systems that must meet loads during the charging period, such as in hospitals, data centers, etc. Control sequences for this mode generally operate all designated generation equipment at its maximum capacity. Capacity that is not needed to meet the load is diverted to

charging storage. Depending on the system design, the load may be piped in series or in parallel with the storage tank. Some systems may have unique requirements in this mode to allow both charging storage and distribution of capacity to meet the load. For example, for an ice storage system using a heat exchanger between a glycol/water mixture and chilled-water loop, the designer may need to address freeze protection on the chilled-water loop side of the heat exchanger.

Meeting Load from Discharging Only. A control sequence for the discharging-only mode (full storage or load shifting) is generally straightforward. The generating equipment is not operated and the entire load is met from the storage system.

Meeting Load from Discharging and Direct Equipment Operation. Control sequences for this mode, used in partial storage operation, must regulate the portion of the load at any time that will be met from storage and the proportion that will be met from direct generation. These control sequences are typically more complex, because more variables come into play in selecting what equipment to operate and at which capacity. These sequences have generally been applied to cool storage systems, although they could be equally applied to heat storage systems. The discussion here is based on cool storage applications. There are three common control sequences used for this mode: chiller-priority, storage-priority, and constant-proportion control.

Chiller-priority control includes operating the chilling equipment, up to the designated available capacity, to meet loads. Cooling loads in excess of this capacity are then met by the storage system. If a demand limit is in place, either on the facility, cooling plant, or individual chilling equipment, the available chilling equipment capacity can be less than the maximum system capacity.

Chiller-priority control can be implemented with any storage configuration; however, it is most commonly applied with the refrigeration equipment in series with and upstream of the storage components. A simple implementation method is to set both the chiller and storage discharge temperature set points equal to the desired system supply water temperature. When the load is less than that available from the cooling equipment, the equipment operates as required to maintain the set point. When the system load exceeds the available cooling equipment capacity, the supply temperature increases above its set point, which requires some flow to be diverted through the storage system to satisfy the load. It is important to note that sensing errors in downstream temperature measurement may cause the unintentional use of storage before the available equipment capacity has been fully used. When premature depletion happens, the usable storage capacity is not available when it was intended and originally scheduled, thereby resulting in a demand penalty, which will show up on the utility bill.

Storage-priority control meets the load from storage up to its available maximum discharge rate. When the load exceeds this discharge rate, the cooling equipment must operate to meet the remaining load. A storage-priority control sequence must ensure that the storage system is not depleted prematurely during the discharge cycle. Failure to properly control or limit the maximum discharge rate could result in loss of control of the cooling load, unexpected demand charges, or both. Load forecasting is required to optimize the benefits of this control method. Chapter 41 describes a method for forecasting diurnal energy requirements. Simpler storage-priority control sequences have also been used that include using constant system discharge rates, predetermined system discharge rate schedules, or other load predictive and control methodologies.

Constant-proportion control or **proportional control** sequences divide the load between cooling equipment and storage. The load may be divided equally or in some other specific proportion that can then be changed in response to changing conditions. Limits on the storage system discharge rate or a demand-limiting requirement on the cooling equipment, plant or facility wide, may be applied in determining these proportions.

Demand-limiting control may be applied to any of the aforementioned sequences. This control method attempts to limit the facility or cooling plant demand by either setting a maximum capacity above which the cooling equipment cannot operate or by adjusting the cooling equipment discharge temperature set point. Because chiller demand can be a significant portion of overall system demand, large demand savings are possible with this control sequence. The demand limit may be a fixed value or may change in response to predefined changes in specific conditions. Demand limiting is generally most effective when chiller capacity is controlled in response to the total demand for a facility at its billing meter. A simpler approach, which generally results in reduced demand savings, is to limit chiller capacity based on its electric demand without consideration of the facility's demand.

The storage system discharge rate may also be limited, similar to the approach taken with chiller demand limiting. Such a limit is typically used with storage priority control to ensure that sufficient capacity is available for the entire discharge cycle. The discharge rate limit may change with time based on changing conditions. The discharge rate limit can be defined as the maximum instantaneous cooling capacity supplied from the storage system. Alternatively, it may be expressed as the maximum discharge flow rate through the storage system or the minimum mixed-fluid temperature in the common discharge of the storage system and the associated bypass.

Operating strategies that continually seek to optimize system operation frequently recalculate the demand and discharge limits during the discharge period.

Nearly all partial-storage system sequences can be described by indicating (1) whether chiller-priority, storage-priority, or proportional control is to be used; and (2) by specifying the applicable cooling equipment demand limit and storage system discharge rate limit.

Applicable utility rates and system efficiency in the various operating modes ultimately determine the selection of the preferred control sequences. If on-peak energy cost is significantly higher than off-peak energy cost, use of stored energy should be maximized during on-peak period(s), and a storage-priority sequence is appropriate. If on-peak energy cost is not significantly more than off-peak energy cost, a chiller-priority sequence is appropriate. When demand charges are high, some type of demand-limiting control scheme should be implemented.

Control Strategies

A thermal storage **control strategy** is the sequence of operating modes implemented under specific conditions of load, weather, season, etc. For example, a control strategy for a summer design day might specify a discharging mode, using storage-priority control during daytime on-peak hours to minimize or eliminate on-peak chiller operation. A winter day control strategy for the same system might use a chiller-priority discharge mode to minimize the storage system operation, because the utility rates are normally close to the same value day and night, thereby negating much of the benefit of thermal storage.

Operating Strategies

It is important to distinguish between the operating strategy, which defines the higher-level logic by which the system operates, and the various control strategies, which implement the specific operating modes. The operating strategy outlines the overall method of control of the thermal storage system necessary to meet the design intent. The operating strategy determines the logic that dictates when each operating mode is to be energized, as well as the control strategy that is implemented in each mode.

Dorgan and Elleson (1993) used the term "operating strategy" to refer to full-storage and partial-storage operation. That discussion focused on design-day operation and did not discuss operation

Table 3   Recommended Accuracies of Instrumentation for Measurement of Cool Storage Capacity

	Temperature, °F	Temperature Differential, °F	Flow Rate, % of reading
Accuracy	±0.3	±0.2	±5%
Precision	±0.2	±0.15	±2%
Resolution	±0.1	±0.1	±0.1%

Notes: *Accuracy* is an instrument's ability to repeatedly indicate the true value of the measured quantity. *Precision* is closeness of agreement among repeated measurements of the same variable. *Resolution* is the smallest repeatable increment in the value of a measured variable that can be accurately measured and reported by an instrument. Values stated are maximum acceptable deviations of sensed and transmitted value from actual value, as measured by a sensor meeting industry standard for testing instrumentation and that is certified periodically to ensure its own accuracy. See Chapter 14 of the 2005 *ASHRAE Handbook—Fundamentals* for more information on instrumentation and measurement principles.

under all conditions. For example, a system designed for partial-storage operation on the design day may operate under a full-storage strategy during other times of the year.

Operating strategies that use sophisticated control routines to optimize the use of storage have been investigated (Drees 1994; Henze et al. 2005). The cost savings benefits of such optimal strategies are often small in comparison to well-designed basic strategies that rely on simpler control routines.

Instrumentation Requirements

The control system for a thermal storage system must include at least measurement points for the following fluid temperatures:

- Entering and leaving chiller(s)
- Entering and leaving storage
- To and from load

In addition, the system should include the ability to measure flow rates at the chiller(s), storage, and load, as well as electric power to the chiller(s) and auxiliaries. Some method of measuring the current storage inventory is also necessary.

Systems with control strategies that rely on measurement of load and capacity may require flow and temperature sensors of higher quality than those normally provided with HVAC control systems. The more accurate instruments are readily available, the cost above standard sensors is nominal compared to the overall cost of the total control system, and the benefits realized are extremely valuable over the life of the system. The accuracy requirements must be included in the specifications to ensure that appropriate instrumentation is provided. Field validation is recommended.

For most applications, the recommended sensor accuracies listed in Table 3 provide an uncertainty of under ±10% in cool storage capacity measurements. When accuracy requirements are critical, the design team should carry out an uncertainty analysis to determine the required accuracy of individual sensors. Note that the accuracy of the system for transmitting and reporting the measured quantities must also be considered. It is not wise to assume that all systems provide the same level of accuracy, regardless of the cost of the system or the components.

If the control system is to be used for performance monitoring, it should be selected for its ability to

- Collect and store required amount of trend log data without interfering with system control functions
- Report averages of measured quantities over a selected interval
- Calculate amount of cooling supplied to or from load, chillers, and storage
- Provide trend log reports in custom formats to fit users' needs
- Provide maximum daily cooling water temperature provided to load, and time of occurrence
- Provide maximum daily water temperature provided from storage to load, and time of occurrence

OTHER DESIGN CONSIDERATIONS

Hydronic System Design for Open Systems

For reasons of cost and ease of construction, large ice storage and chilled-water storage tanks are typically vented to the atmosphere. When, as frequently occurs, the fluid level in a storage tank is not the highest point in the system, special attention must be paid to pumping system design to ensure that the different pressure levels are maintained and the tank does not overflow. The overview of possible transfer pumping interfaces presented in this chapter identifies the main issues requiring attention in open-system design and some ways they have been successfully addressed in chilled-water storage systems installed to date. The design guide of Gatley and Mackie (1995) provides a comprehensive discussion of open systems.

Cold-Air Distribution

The low cooling supply temperatures available from ice storage and some other cool storage media allow the use of lower supply air temperatures, which permits decreased supply air volume and smaller air distribution equipment. This approach leads to the following benefits:

- **Reduced mechanical system costs**, particularly for fans and ductwork. The cost for electrical distribution to fans may also be reduced.
- **Reduction of 30 to 40% in fan electrical demand and energy consumption.**
- **Reduced space requirement for fans and ductwork.** In some cases, this can reduce the required floor-to-floor height, with significant savings in structural, envelope, and other building systems costs. In this case, if the building is being built in an area with strict height limitations, additional floor(s) may be possible, thereby greatly increasing the value of the building.
- **Improved comfort with lower space relative humidity.** Laboratory research has shown that people feel cooler and more comfortable at lower relative humidities, and air is judged to be fresher with a more acceptable air quality, as experienced with cold-air distribution systems.
- **Increased cooling capacity for existing distribution systems.** By reducing supply air temperatures, owners can avoid the expense of replacing or supplementing existing air distribution equipment.

The cost reduction enabled by cold-air distribution can make thermal storage systems competitive with nonstorage systems on an initial-cost basis (Landry and Noble 1991; Nelson 2000).

Lower supply temperatures provide greater benefits from reduced size and energy use; however, this technology involves greater departure from standard engineering practice and requires increased attention to condensation control and other critical considerations. Nominal supply air temperatures as low as 42°F can be achieved with 36°F fluid, which can be supplied from ice storage; however, 45°F supply air is a more efficient target. Supply air temperatures of 48 to 50°F can be achieved with minimal departure from standard practice and still provide significant cost reductions. The optimum supply air temperature should be determined through an analysis of initial and operating costs for the various design options.

The minimum achievable supply air temperature is determined by the chilled-fluid temperature and temperature rise between the cooling plant and terminal units. With ice storage systems, in which the cooling fluid temperature rises during discharge, the design fluid supply temperature should be based on the flow-temperature profiles of the secondary fluid and the characteristics of the selected storage device.

A heat exchanger, which is sometimes required with storage devices that operate at atmospheric pressure or between a secondary coolant and chilled-water system, adds at least 2°F to the final

chilled-fluid supply temperature above the generated temperature. The temperature difference between supply fluid entering the cooling coil and air leaving the coil is generally 6 to 10°F. A closer approach (smaller temperature differential) can be achieved with more rows or a larger face area on the cooling coil, but extra heat transfer surface to provide a closer approach is often uneconomical. A 3°F temperature rise in the air between the coil discharge and supply to the space can be assumed for preliminary design analysis. This is from heat gain in the duct between the cooling coil and terminal units. With careful design and adequate insulation, this rise can be reduced to as little as 1°F.

For a given supply air volume, the desired face velocity determines the size of the coil. Coil size determines the size of the air-handling unit. A lower face velocity achieves a lower supply air temperature, whereas a higher face velocity results in smaller equipment and lower first costs. Face velocity is limited by the possibility of moisture carryover from the coil. For cold-air distribution, the face velocity should be 350 to 450 fpm, with an upper limit of 550 fpm

Cold primary air can be tempered with room air or plenum return air using fan-powered mixing boxes or induction boxes. The energy use of fan-powered mixing boxes is significant and negates much of the savings from downsizing central supply fans (Elleson 1993; Hittle and Smith 1994). Diffusers designed with a high ratio of induced room air to supply air can provide supply air directly to the space without drafts, thereby eliminating the need for fan-powered boxes.

If the supply airflow rate to occupied spaces is expected to be below 0.4 cfm/ft^2, fan-powered or induction boxes should be used to boost the air circulation rate. At supply airflow rates of 0.4 to 0.6 cfm/ft^2, a diffuser with a high ratio of induced room air to supply air should be used to ensure adequate dispersion of ventilation air throughout the space. A diffuser that relies on turbulent mixing rather than induction to temper the primary air may not be effective at this flow rate.

Cold-air distribution systems normally maintain space relative humidity between 30 and 45%, as opposed to the 50 to 60% rh generally maintained by other systems. At this lower relative humidity level, equivalent comfort conditions are provided at a higher dry-bulb temperature. The increased dry-bulb set point generally results in decreased energy consumption.

In most buildings using cold-air distribution, relative humidity is reduced throughout the building. At these low dew-point conditions, the potential for condensation is no greater than in a higher-humidity space with higher supply air temperatures. However, spaces that may be subject to infiltration of humid outside air (e.g., entryways) may need tempered supply air to avoid condensation.

Surfaces of any equipment that may be cooled below the ambient dew point, including air-handling units, ducts, and terminal boxes, should be adequately insulated. All vapor barrier penetrations should be sealed to prevent migration of moisture into the insulation. Prefabricated, insulated round ducts should be insulated externally at joints where internal insulation is not continuous. Access doors should also be well insulated.

Duct leakage is undesirable because it represents cooling capacity that is not being delivered to the conditioned space. In cold-air distribution systems, leaking air can cool nearby surfaces to the point that condensation forms, which can lead to many other problems. Designers should specify acceptable methods of sealing ducts and air-handling units, and establish allowable leakage rates and test procedures. During construction, appropriate supervision and inspection personnel should ensure that these specifications are being followed.

The same indoor air quality considerations must be applied to a cold-air distribution design as for a higher-temperature design. The required volume of outdoor ventilation air is normally the same, although the percentage is higher for cold-air distribution systems, because the total air volume is lower. As with any design, systems serving multiple spaces with different occupant densities may require special attention to ensure adequate outside air is delivered to each space.

Designs using reheat should incorporate strategies to reset the supply air temperature at low cooling loads, to avoid increased energy use associated with reheating minimum supply air quantities.

Storage of Heat in Cool Storage Units

Some cool storage installations may be used to provide storage for heating duty and/or heat reclaim. Many commercial buildings have areas that require cooling even during the winter, and the refrigeration plant must, therefore, be in operation year-round. When cool storage is charged during the off-peak period, the rejected heat may be directed to the heating system or to storage rather than to a cooling tower. Depending on the building loads, the chilled water or ice could be considered a by-product of heating. One potential use of the heat is to provide morning warm-up on the following day.

Heating, in conjunction with a cool storage system, can be achieved using heat pumps or heat reclaim equipment, such as double-bundle condensers, two condensers in series on the refrigeration side, or a heat exchanger in the condenser water circuit. Cooling is withdrawn from storage as needed; when heat is required, the cool storage is recharged and used as the heat source for the heat pump. If needed, additional heat must be obtained from another source because this type of system can supply usable heating energy only when the heat pump or heat recovery equipment is running. Possible secondary heat sources include a heat storage system, solar collectors, or waste heat recovery from exhaust air. When more cooling than heating is required, excess energy can be rejected through a cooling tower.

Individual storage units may be alternated between heat storage and cool storage service. Stored heat can be used to meet the building's heating requirements, which may include morning warm-up and/or evening heating, and stored cooling can provide midday cooling. If both the chiller and the storage are large enough, all compressor and boiler operation during the on-peak period can be avoided, and the heating or cooling requirements can be satisfied from storage. This method of operation replaces the air-side economizer cycle that uses outside air to cool the building when the enthalpy of outside air is lower than that of return air.

The extra cost of equipping a chilled-water storage facility for heat storage is small. Necessary plant additions may include a partition in the storage tank to convert a portion to warm-water storage, some additional controls, and a chiller equipped for heat reclaim. The additional cost may be offset by savings in heating energy. In fact, adding heat storage may increase the economic advantage of installing cool storage.

Care should be taken to avoid thermal shock when using cast-in-place concrete tanks, one specific type of concrete tank. Tamblyn (1985) showed that the seasonal change from heat storage to cool storage caused sizable leaks to develop if the cooldown period was fewer than five days. Raising the temperature of a cast-in-place concrete tank causes no problems because it generates compressive stresses, which concrete can sustain. Cooldown, on the other hand, causes tensile stresses, under which cast-in-place concrete has low strength and, therefore, is more prone to failure. However, precast prestressed concrete tanks are not prone to this type of failure because the walls of the tank are in constant compression from the prestressing wires that are in tension and encircle the exterior of the tank walls.

System Interface

Open Systems. Chilled-water, salt and polymeric PCMs, external-melt ice-on-coil, and ice-harvesting systems are all open (vented to the atmosphere) systems. Draindown of water from the

higher-pressure system back into the storage tank(s) must be prevented by isolation valves, pressure-sustaining valves, or heat exchangers. Because of the potential for draindown, the open nature of the system, and the fact that the water being pumped may be saturated with air, the construction contractor must follow the piping details carefully to prevent pumping or piping problems.

Closed Systems. Closed systems normally circulate an aqueous secondary coolant (25 to 30% glycol solution) either directly from the storage circuit to the cooling coils or to a heat exchanger interfaced with the chilled-water system. A domestic water makeup system should not be the automatic makeup to the secondary coolant system. An automatic makeup unit that pumps a premixed solution into the system is recommended, along with an alarm signal to the building automation system to indicate makeup operation. The secondary coolant must be an industrial solution (not automotive antifreeze) with inhibitors to protect the steel and copper found in the piping. The water should be deionized; portable deionizers can be rented and the solution can be mixed on site. A calculation, backed up by metering the water as it is charged into the piping system for flushing, is needed to determine the specified concentration. Premixed coolant made with deionized water is also available, and tank truck delivery with direct pumping into the system is recommended on large systems. An accurate estimate of volume is required.

Insulation

Because the chilled-water, secondary coolant, or refrigerant temperatures are generally 10 to 20°F below those found in nonstorage systems, special care must be taken to prevent damage. Although fiberglass or other open-cell insulation is theoretically suitable when supplied with an adequate vapor barrier, experience has shown that its success is highly dependent on workmanship. Therefore, a two-layer, closed-cell material with staggered, carefully sealed joints is recommended. A thickness of 1.5 to 2 in. is normally adequate to prevent condensation in a normal room. Provisions should be made to ensure that the relative humidity in the equipment room is less than 80%, either by heating or by cooling and dehumidification.

Special attention must be paid to pump and heat exchanger insulation covers. Valve stem, gage, and thermometer penetrations and extensions should be carefully sealed and insulated to prevent condensation. PVC covering over all insulation in the mechanical room improves appearance, provides limited protection, and is easily replaced if damaged. Insulation located outdoors should be protected by an aluminum jacket.

COST CONSIDERATIONS

Cool storage system operating costs are lower in general than those of nonstorage systems. On-peak demand charges are reduced, and energy use is shifted from expensive on-peak periods to less expensive off-peak times.

Operating cost estimates can be developed to varying levels of detail and accuracy. In some cases, simple estimates based on peak demand savings may be adequate. At the other extreme, an hour-by-hour analysis, including energy consumption of chillers, pumps, and air-handler fans, may be desirable.

In many applications, most of the operating cost savings come from reductions in demand charges. Demand savings for each month of the year are calculated based on estimates or calculations of load variations throughout the year and on knowledge of system control strategies during nonpeak months. It is generally straightforward to calculate annual demand savings by repeating the design-day analysis with appropriate load profiles and rate structures for each month.

For some applications, particularly where there is a large differential between on- and off-peak energy costs, chiller energy savings

are significant. For many cool storage designs, pumping energy savings are also important. Added savings in fan energy should also be considered if cold-air distribution is used.

Annual energy savings can be estimated using energy modeling programs. However, programs currently available typically do not model the unique performance characteristics of the various storage technologies. Most programs do not consider the interaction between chiller and storage performance; the effects of chiller-upstream or chiller-downstream configuration; or the performance impacts of chiller-priority, storage-priority, and demand-limiting control strategies. In some cases, these shortcomings may offset the benefits of performing a detailed computer simulation. Additional information on calculating annual energy use is given in Dorgan and Elleson (1993) and Elleson (1997).

MAINTENANCE CONSIDERATIONS

Following the manufacturer's maintenance recommendations is essential to satisfactory long-term operation. These recommendations vary, but their objective is to maintain the refrigeration equipment, refrigeration charge, coolant circulation equipment, ice builder surface, water distribution equipment, water treatment, and controls so they continue to perform at or near the same level as they did when the system was commissioned. The control systems must be kept in calibration, water and heat transfer fluids must be treated regularly, and any valves or pumps must be maintained per manufacturer's instructions. Monitoring ongoing performance against commissioned kilowatt-hours per ton-hour of cooling capacity delivered gives a continuing report of the system's dynamic performance.

The heat transfer fluid vendor should be consulted for information on treating the heat transfer fluid. Most heat transfer fluids are supplied with required additives by the manufacturer and require annual analysis.

History of previously constructed systems indicates the importance of careful observance to the following items:

- Start-up in accordance with manufacturer's directions
- Introduction of additives in accordance with manufacturer's directions
- Regular inspections (confined-space entry program should be reviewed and in place): visual periodic electronic monitors and/or divers
- Older systems: as applicable, review for upgrade modifications to (1) diffuser system and (2) control system
- Interior and exterior materials (corrosive and noncorrosive) (piping, fasteners, supports, etc.): check for container wall under-cover insulation corrosion; repair damaged insulation
- Appurtenances (vents, ladders, overflows, temperature sensors): all well secured and sensors calibrated
- Electrical systems: well secured and connections secure

Water Treatment

Water treatment for thermal storage systems is not fundamentally different from water treatment for nonstorage systems, except that there is generally a greater volume of water to be treated. Although water close to freezing has very low corrosion, treatment for biological matter, scale, and corrosion must be used. Initially, many water treatment representatives felt the systems required far more chemical treatment than actually required. This was evidently because they were considering the "open" nature of the system to be a large surface area, with the associated large volume of chemical evaporation. Ahlgren (1987, 1989) provides details on water treatment for thermal storage systems. For further information, see Chapter 48.

Cleaning. Starting with a clean system at start-up minimizes problems throughout the life of the system. Ahlgren (1987) provides the following list of major steps in preoperational cleaning:

1. Remove all extraneous loose debris, construction material, trash, and dirt from tanks, piping, filters, etc., before the system is filled. Removing as much dry material as possible prevents transfer to hard-to-reach portions of the system.
2. Flush the fill water pipeline separately to drain. If a new water line has been installed, be sure that rust and debris from it is not washed into the thermal storage system.
3. Fill the system with soft, clean, fresh water. Open all system valves and lines to get thorough, high-velocity recirculation.
4. Add prescribed cleaning chemicals to circulating water. Most cleaners are a blend of alkaline detergents, wetting agents, and dispersants. Be sure cleaning chemical is dissolved and distributed thoroughly so it does not settle out in one part of the system.
5. Circulate cleaning solution for manufacturer's recommended time, frequently 8 to 24 h. Check during recirculation for any plugging of filters, strainers, etc.
6. While water is recirculating at a high rate, open drain valves at the lowest points in the system and drain cleaning solution as rapidly as possible. Draining while under recirculation prevents settling of solids in remote portions of the system.
7. Open and inspect system for thoroughness of cleaning. Refill with water and start rinse recirculation. If significant amounts of contaminants are still present, repeat cleaning and draining procedure until clean.
8. When cleaning has been thoroughly accomplished, refill system with fresh water for recirculation rinse. Drain rinse water and add fresh makeup, repeating the process until all signs of cleaning chemicals have been removed.
9. System is now in a clean, unprotected state. Fill with makeup water and proceed with passivating to develop protective films on all metallic surfaces.

Caution: (1) Water containing any contaminants, detergent, or disinfectant must be drained to an appropriate site. Check with local authorities before draining the system. (2) Water should be treated as soon as possible after cleaning the system. Cleaning removes any protective films from equipment surfaces, leaving them susceptible to corrosion. Especially when there is an extended period between cleaning and system start-up, corrosion and biofouling can become significant problems if water treatment is not initiated promptly.

Open Systems. Water treatment must be given close scrutiny in open systems. Although the evaporation and concentration of solids associated with cooling towers does not occur, the water may be saturated with air, so the corrosion potential is greater than in a closed system. Treatment against algae, scale, and corrosion must be provided. Water treatment must be operational immediately after cleaning. Corrosion coon assemblies should be included to monitor treatment effectiveness. Water testing and service should be performed at least once a month, preferably weekly immediately following initial start-up, by the water treatment supplier.

Systems open to the atmosphere require periodic applications of a biocide. Potable water is usually of acceptable quality for storage tanks that are filled at the installation site. Where the water is in contact with either a metallic heat exchanger or tank, additional treatment may be needed to regulate pH, chlorides, or other water quality parameters.

Closed Systems. The secondary coolant should be pretreated by the supplier. A complete analysis should be done annually. Monthly checks on the solution concentration should be made using a refractive indicator. (Automotive-type testers are not suitable.) For normal use, the solution should be good for many years without adding new inhibitors. However, provision should be made for injection of new inhibitors through a shot feeder if recommended by the manufacturer. The need for filtering, whether by including a filtering system or filtering the water or solution before it enters the system, should be carefully considered. Combination filter/feeders

and corrosion coupon assemblies may be needed to monitor the effect of the solution on the copper and steel in the system.

COMMISSIONING

Commissioning is a process whereby all of the subsystems and components of the system are incorporated into a whole system that functions according to the design intent. The complete commissioning process, as outlined in ASHRAE *Guideline* 1, begins in the program phase and lasts through training of the building operators and the first year of operation of the building. Commissioning strives for improved communication among parties to the design procedure, providing for clear definition of the functional needs of the HVAC system, and documentation of design criteria, assumptions, and decisions.

Cool storage systems can especially benefit from commissioning. Some storage systems, particularly partial-storage systems, may have less reserve cooling capacity than nonstorage systems. A nonstorage system has excess capacity in every hour that is not a design hour. Storage systems benefit from the use of stored cooling to achieve a closer match of total capacity to total load. These benefits are achieved at the price of some additional complexity to control the inventory of stored cooling, and a reduced safety factor. Therefore, there is a need for increased care in design, installation, and operation, which the commissioning process helps to ensure.

Commissioning should also provide documentation of actual system capacities, which allows control strategies to be optimized to take full advantage of system capabilities.

Additional information on the commissioning process is given in Chapter 42, and detailed information on commissioning and performance testing for cool storage systems is provided in ASHRAE *Guideline* 1 and *Standard* 150, and by Elleson (1997).

Statement of Design Intent

The statement of design intent defines in detail the performance requirements of the cool storage system. It is the master reference document that shapes all future work and is the benchmark by which success of the project is judged. The process of defining the design intent should begin as early as possible in the program phase, and continue throughout the design phase.

The initial statement of design intent is prepared from information developed in the owner's program and the results of the feasibility study. It describes the facility's functional needs, as well as the owner's requirements for environmental control and system performance. These items include

- Temperature and relative humidity requirements
- Cooling load parameters
- Acceptable hours (if any) that loads may exceed system capacity
- Occupancy schedules
- Reliability or redundancy requirements
- Needs for operational flexibility
- Financial criteria
- Energy performance criteria
- Demand shift

During the design phase, the following items are added:

- Narrative description of the system
- Performance goals for energy consumption and electric demand
- Hourly operating profile for design day and minimum-load day
- Schematic diagram of piping system, including cool storage system
- Description of control strategies for all possible modes and conditions

As the design develops, these items are refined and expanded, so the final statement of design intent provides a detailed description of the intended configuration, operation, and control of the system.

Commissioning Specification

The commissioning specification defines the contractual relationships by which the final system is brought into conformance with the design intent. It delineates the responsibilities of each party; specifies the requirements for construction observation, start-up, and acceptance testing; and defines the criteria by which the performance of the system is evaluated.

ASHRAE *Guideline* 1 provides additional details on and a sample of a commissioning specification.

Required Information

Certain system-specific design information must be assembled before running performance tests. These data are required to determine the test conditions and requirements for a specific system. The following information must be supplied:

- Load profile against which storage device or system is to be tested
- Tests to be performed; users may elect to perform one or more individual tests
- Boundary of system or portion of system to be tested by system capacity test
- Components with energy inputs to be included in system efficiency test
- System parameters, such as
  - Maximum usable discharge temperature
  - Maximum usable cooling supply temperature
  - Criteria for determining fully charged and fully discharged conditions
  - Maximum amount of time available for charging storage

Much of this information is normally defined in the statement of design intent.

Performance Verification

Before performance testing, verification should confirm that each component has been installed properly and that all individual components, equipment, and systems actually function in accordance with the contract documents and with the manufacturers' specifications. This verification should include items such as the following:

- Chillers maintain correct set points for each operating mode.
- Chiller capacity is within specified tolerances.
- Pumps, valves, and chillers sequence correctly in each operating mode and when changing between modes.
- Glycol concentration is as specified.
- Storage tank inlet and outlet temperatures are correct during both charging and discharging modes.
- Controllers and control valves and dampers maintain temperature set points.
- Flow switches function correctly.
- Flow rates are as reported in testing, adjusting, and balancing (TAB) report.
- Flow meters and temperature sensors report accurate measurements.
- Pressure-sustaining valve maintains correct pressure.
- Heat exchangers provide and maintain specified differential temperatures.
- Freeze protection sequence operates correctly.

Functional performance testing demonstrates that performance of the system as a whole satisfies the statement of design intent and contract documents. The functional performance test determines whether all components of the system function together, as designed, to meet the cooling load while satisfying the targets for electric demand and energy consumption. Functional performance testing is intended to answer basic questions such as the following:

- Does system function according to statement of design intent?
- Does system meet each hour's instantaneous load, at required fluid temperature?
- What is usable storage capacity of the storage tanks?
- What is available system capacity to meet the load, instantaneous and average for the day?
- What is system's efficiency in meeting the load, instantaneous and average for the day?
- What is daily tank standby loss?
- What is chiller capacity in charge mode and in direct cooling mode?

Functional performance testing also helps establish the final operating set points for control parameters such as chiller demand limit, ice-making cutout temperature, etc.

Because the performance of a cool storage system depends on the load to which it is subjected, the system must be tested with a design cooling load profile, or an equivalent profile.

ASHRAE *Standard* 150 provides detailed test methods for accurately determining a system's ability to meet a given cooling load. The standard requires some documentation before a performance test is carried out, including the design load profile, criteria for determining the fully charged and fully discharged conditions, and a schematic diagram of the system illustrating intended measuring points. This standard defines procedures for determining the charge and discharge capacities of a storage device and the total capacity and efficiency of the entire system. The starting and ending points for the performance tests are defined in terms of two distinctive states of charge: fully charged and fully discharged.

The **fully charged** condition is the state at which, according to the design, no more heat is to be removed from the tank. This state is generally reached when the control system stops the charge cycle as part of its normal control sequence, or when the maximum allowable charging period has elapsed.

The **fully discharged** condition is the state at which no more usable cooling capacity can be recovered from the tank. This condition is reached when the fluid temperature leaving the tank rises above the maximum usable chilled-water supply temperature.

Performance testing of cool storage systems tends to be more susceptible to sensor errors than testing of nonstorage systems, because data must be collected and accumulated over an extended time. Sensor accuracy should be verified in the field, particularly when the results of performance tests will have contractual or financial implications. Elleson et al. (2002) discuss verifying sensor accuracy.

Sample Commissioning Plan Outline for Chilled-Water Plants with Thermal Storage Systems

The following is an outline of a generic commissioning plan for cool storage systems.

A. Identify owner project requirements (OPR).

1. Site objectives.
2. Functional uses and operational capabilities.
3. Indoor environmental requirements.
4. Environmental and utility cost, and energy and demand savings goals.
5. Level of control desired.
6. Training expectations.
7. Expected/current capabilities of owner's O&M staff.
8. Include specific measurement performance criteria, such as discharge rate, daily cooling capacity available from storage, capacity shifted from peak to off-peak, and average daily plant performance (be explicit as to what equipment is to be included).
9. If project is a retrofit, identify current systems and their operating schedules.

B. Identify economic assumptions; perform economic feasibility analysis.

C. Identify approximate schedule of operation.

D. Define expected scope of commissioning services, systems, and equipment included, as well as commissioning team members.

E. Conduct commissioning kick-off meeting: establish schedule for future meeting; discuss how performance criteria are to be verified, monitored, and maintained.

F. Develop design intent document (OPR).

G. Conduct design review: focus on adherence to OPR, and efficacy of design parameters, including design load profile, clarity of control sequence descriptions, and maintainability of design.

H. Develop/review commissioning related specifications: include project-specific training requirements and required programming of operational block trends.

I. Conduct prebid meeting: identify commissioning requirements and expectations with potential bidders.

J. Review submittal for adherence to specification and OPR.

K. Negotiate desired exceptions to specification.

L. Prepare site specific checks and test procedures. Potential checks and tests to consider include
   1. Verify proper placement and calibration of critical sensors.
   2. Verify proper setup of valve and damper actuators.
   3. Verify proper programming of schedules, set points, key sequences of control, and graphics. Verify proper implementation of sensor calibration parameters and PID loop tuning parameters.
   4. Verify communication speeds, system response times, and maximum trending capability.
   5. Use operational trends to verify proper operation of economizers, set points, schedules, and staging.
   6. Specialized checks and tests include

   - Verify proper concentration of secondary coolant
   - Restart after power outage
   - Chiller capacity
   - Cooling capacity available from storage
   - Daily plant performance

M. Review operational block trend data. Program new trends as necessary. Conduct installation checks and functional testing. Develop summary of activities and key findings in problem log format. Discuss results with client and contractor. After contractor has made necessary corrections, review corrections and retest as necessary. Note that costs for retesting should be obligation of contractor.

N. Review as-builts and O&M documentation: be sure that clear operating plan is developed and available to operating staff.

O. Conduct/participate in/verify/document facilities staff and user training.

P. Prepare commissioning report: identify unresolved issues.

Q. Prepare systems manual.

R. Complete off-season testing and update systems manual with relevant operation and maintenance information as required.

S. Conduct one-year warranty review.

T. Conduct project wrap-up meeting. Finalize accountability requirements for maintaining performance.

GOOD PRACTICES

Elleson (1997) explored factors determining the success of cool storage systems and identified the following actions that contribute to successful systems:

- Calculating an accurate load profile
- Using an hourly operating profile to size and select equipment
- Developing a detailed description of the control strategy
- Producing a schematic diagram
- Producing a statement of design intent
- Using safety factors with care

- Planning for performance monitoring
- Producing complete design documents
- Retaining an experienced cool storage engineer to review the design before bidding the project

A number of pitfalls were also identified that can jeopardize success:

- Owner not willing to commit resources to support high-quality design process
- Owner does not identify and communicate all requirements for cooling system early in project
- Economic value of project not presented in appropriate financial terms; project goes unfunded
- Project justified on basis of incomplete or inaccurate feasibility study
- Assumptions made in feasibility study not documented and not verified in design phase
- Design intent for system not updated as design progresses, or recorded in contract documents
- System design based on estimates and assumptions rather than on engineering analysis
- Design not reviewed by qualified, independent reviewer
- Complete description of intended control strategies is not included in specifications
- Performance testing not required in contract documents, or test requirements not adequately defined
- Equipment submittals not reviewed for required conformance with specifications, or inadequate equipment substituted to reduce costs
- Operation and maintenance personnel not included in design process, or operator training is neglected
- Owner not willing to complete acceptable level of commissioning before accepting system for day-to-day use
- Owner not willing to support qualified, well-trained staff to achieve optimum performance

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CHAPTER 35

ENERGY USE AND MANAGEMENT

ENERGY management in buildings is the control of energy use and cost while maintaining indoor environmental conditions to meet comfort and functional needs. Energy efficiency improvements need not sacrifice any functionality of the facility. This chapter provides guidance on establishing and implementing an effective, ongoing energy management program, as well as information on planning and implementing energy management projects.

Good energy management has the goal of reducing energy expenses to the lowest level possible without sacrificing comfort, productivity, or functionality. The energy manager should understand how energy is used in the building, to manage energy use and costs effectively. There are opportunities for savings by reducing the unit price of purchased energy, and by improving the efficiency and reducing the use of energy-consuming systems.

Water/sewer costs and use may be included in the energy management activity. This could be called "utility management," but "energy management" is used in this chapter.

ENERGY MANAGEMENT

The specific processes by which building owners and operators control energy consumption and costs are as variable as their building types. Many buildings, such as residences and small retail businesses, usually involve the efforts of one person. Energy management procedures should be as simple, specific, and direct as possible. General advice, such as from utility energy surveys or state or provincial energy offices, can provide ideas, but these must be evaluated to determine whether they are applicable to a specific building. Often, owners and operators of smaller buildings only need advice about specific energy management projects (e.g., boiler replacement, lighting retrofit).

On the other hand, very large and complex facilities, such as hospital or university campuses, industrial complexes, or large office buildings, usually require a team effort and process as represented in Figure 1.

Regardless of the number of people involved or the size and complexity of the facilities, energy management for existing buildings has the same basic steps:

1. An energy manager is usually appointed to oversee the process. Doing so ensures that someone is dedicated to the initiatives and accountable to the company.
2. Early communication helps with input and feedback to the other steps of the process.
3. Establish an energy accounting system that records energy and water consumption and costs, thus providing data for analyzing energy use and identifying energy conservation opportunities. It also should include comparisons with energy use and costs of other similar buildings, for use in benchmarking and setting energy performance goals.

The preparation of this chapter is assigned to TC 7.6, Systems Energy Utilization.

Designate and Define Energy Manager Responsibilities and Qualifications

Establish Communications

Establish Energy Accounting System

Analyze Energy Data

Perform Energy Surveys and Audits

Improve Discretionary Operations

Evaluate Energy Conservation Opportunities and Prioritize

Implement Energy Conservation Measures

Monitor Results

Evaluate Success and Establish New Goals

Fig. 1   The Energy Management Process

4. Validate and analyze energy use data.
5. Carry out energy surveys and walk-through audits to provide the information needed to identify low-cost/no-cost operations, maintenance, and energy conservation opportunities relevant to the specific building or buildings. Often, a qualified energy professional is hired to do this.
6. Using the survey results, change how the building is operated, using good judgment to change procedures with energy management in mind.
7. Evaluate energy conservation opportunities for expected savings, estimated implementation costs (including any design work required), risks, and nonenergy benefits (e.g., improved system operation, better indoor comfort). Establish baseline energy use for whole building or individual energy conservation opportunities. Recommend a number of prioritized energy conservation projects for implementation.
8. Implement approved energy conservation measures (ECMs). This includes tendering any projects that must be outsourced.
9. Track trends and monitor results, using the energy accounting system for overall performance supplemented as needed by energy monitoring related to specific projects, and report to senior management.
10. Compare energy performance to past goals, revise as necessary, and develop new goals. Report results to management and tenants. Return to step 7 and continue the process; it requires ongoing diligence to maintain and continually improve energy savings and reduce utility costs.

Each of these energy management program components is discussed in more detail in the following sections.

Because energy management is performed in existing facilities, this chapter focuses mainly on these facilities. ASHRAE *Standard* 100 gives details useful in energy management planning. Information on energy conservation in new design can be found in all volumes of the *ASHRAE Handbook* and in ASHRAE *Standards* 90.1 and 90.2. The area most likely to be overlooked in new design is the ability to measure and monitor energy consumption and trends for each energy use category given in Chapter 40. Additional guidelines for this area can be found in Chapter 17 of the 2005 *ASHRAE Handbook—Fundamentals*.

Organizing for Energy Management

To be effective, energy management must be given the same emphasis as management of any other cost/profit center. In this regard, the functions of top management are as follows:

- Establish the energy cost/profit center
- Assign management responsibility for the program
- Hire or assign an energy manager and provide training as necessary
- Allocate resources
- Ensure that the energy management program is clearly communicated to all departments to provide necessary support for achieving effective results
- Set clear program goals
- Encourage ownership of the program to all levels of the organization
- Set up an ongoing reporting and analysis procedure to monitor the energy management program
- Develop a feedback mechanism to allow revisions to the energy management program in a timely manner

Effective energy management requires that the energy manager (supported by a suitable budget) act and be held accountable for those actions. It is common for a facility to allocate 3 to 10% of the annual energy cost for administration of an energy management program. The budget should include funds for additional personnel as needed, and for continuing education of the energy manager and staff.

Energy Managers

The functions of an energy manager fall into four broad categories: technical, policy-related, planning and purchasing, and public relations. A list of specific tasks and a plan for their implementation must be clearly documented. An energy manager in a large commercial complex may perform most of the following functions; one in a smaller facility may have only a few from each category to consider. Assistance may be needed with some of the tasks listed.

Technical functions

- Conducting energy audits and identifying energy conservation opportunities
- Establishing a baseline from which energy-saving improvements can be measured
- Acting as in-house technical consultant on new energy technologies, alternative fuel sources, and energy-efficient practices
- Evaluating energy efficiency of proposed new construction, building expansion, remodeling, and new equipment purchases
- Setting performance standards for efficient operation and maintenance of machinery and facilities
- Reviewing state-of-the-art energy management hardware
- Reviewing building operation and maintenance procedures
- Implementing energy conservation measures (ECMs)
- Establishing an energy accounting system for continuing analysis of energy use and results of ECMs
- Maintaining effectiveness of ECMs
- Measuring energy use in the field whenever possible to verify design and operating conditions

Policy-related functions

- Fulfilling energy policy established by top management
- Monitoring federal and state (provincial) legislation and regulatory activities, and recommending policy/response on such issues
- Representing the organization in energy associations
- Administering government-mandated reporting programs

Planning and purchasing functions

- Monitoring energy supplies and costs to take advantage of fuel-switching and load management opportunities
- Ensuring that systems and equipment are purchased based on economics, energy requirements, and ability to perform required functions, not simply on lowest initial cost
- Maintaining a current understanding of energy conservation, grant programs, and demand-side management (DSM) programs offered by utilities and agencies
- Negotiating or advising on major utility contracts
- Developing contingency plans for supply interruptions or shortages
- Forecasting short- and long-term energy requirements and costs
- Providing input into utility budgets
- Developing short- and long-term conservation plans and budgets
- Reporting regularly to top management and other pertinent departments (building operations)

Public relations functions

- Making fellow employees aware of the benefits of efficient energy use
- Establishing a mechanism to elicit and evaluate energy conservation suggestions from employees
- Recognizing successful energy conservation projects through awards to plans and employees
- Setting up a formal mechanism for reporting to top management
- Establishing an energy communications network within the organization, including newsletters, bulletins, manuals and conferences
- Making the community aware of the energy conservation achievements of the organization with press releases and appearances at civic group meetings

General Qualifications

- A technical background, preferably in engineering, with experience in energy-efficient design of building systems and processes
- Practical, hands-on experience with systems and equipment
- Goal-oriented management style
- Ability to work with people at all levels, from staff to operations and maintenance personnel to top management
- Technical report-writing and verbal communication skills

Desirable Educational and Professional Qualifications

- Bachelor of science degree, preferably in mechanical, electrical, industrial, or chemical engineering
- Thorough knowledge of the principles and practices of energy resource planning and conservation
- Familiarity with administrative governing organization
- Ability to
  - Analyze and compile technical and statistical information and reports with particular regard to energy usage
  - Establish effective working relationships with other employees and to motivate people
  - Interpret plans and specifications for building facilities
- Knowledge of
  - Resources and information relating to utility rates, energy conservation, and planning
  - Basic types of automatic controls and systems instrumentation
  - Energy-related metering equipment and practices
  - Organization's manufacturing processes

- Building systems design and operation and/or maintenance
- Interest in and enthusiasm for efficient energy use and ability to present ideas to all levels in the organization

If it is not possible to add a full-time, first-line manager to the staff, an existing employee, preferably with a technical background, should be considered for a full- or part-time position and trained to organize an energy management program. Energy management should not be a collateral duty of an employee who is already fully occupied. Another option is to hire a professional energy management consultant to design, implement, and maintain energy efficiency improvements and provide energy accounting. Some energy services companies (ESCOs) and other firms provide energy management services as part of a contract, with payments based on realized savings. Other companies provide energy management services, based on a nominal fee, to assist the energy manager prepare information to be presented to upper management to meet corporate goals.

COMMUNICATIONS

Entering into an energy management process requires careful planning and help from all that operate and use the facility. A communication plan should be reviewed by both the energy manager and senior management. This plan should be reviewed regularly to ensure that the right messages are relayed to the right parties.

The initial communiqué should introduce the effort that will be put forth by the energy manager and building operations staff. It should at the same time express the support of company's executive to ensure the process to be undertaken is not a passing thought. High-level goals should be expressed without initially quantifying them.

Providing early information to tenants and staff is important, because it takes time to change behaviors of people used to operating their lights and equipment in a certain fashion for many years. Once the communication plan is launched, the energy manager should be prepared to answer a variety of questions from different areas of the company.

An effective communication strategy includes some or all of the tasks listed here; the scope depends on the size of the company and its facilities.

- Produce, distribute, and post regular newsletters
- Post energy-saving tips or reminders in conspicuous locations
- Hold seminars with maintenance and cleaning staff to review energy-efficient practices to be followed in daily activities
- Meet with operations staff for training and feedback
- Report regularly to management: monthly updates with annual summaries
- Make frequent reports to operations staff so energy consumption or billing anomalies can be addressed in a timely manner

Message content should be tailored to the specific audience. A tradesperson in the building operations department would routinely be concerned with matters such as temperature setbacks, time clock settings, or light fixture lamp types. Meanwhile, office workers would be more receptive to being informed how much money the company saved on utilities last month, or how much it costs to operate their computer monitors for 50 hours a week.

The more successful communication is, the quicker the energy management activities will become second nature to everyone involved. Diligent, regular reporting promotes accountability and persistence in reducing energy consumption.

ENERGY ACCOUNTING SYSTEMS

Establishing and maintaining an energy accounting system to track energy consumption and costs on a continuing basis is very valuable. It provides energy use data to building occupants, helping them see the results of their conservation efforts and support their continued efforts. It also provides some data needed to confirm savings from specific energy conservation projects. The starting point is gathering energy and related data and evaluating the relative intensity of energy use. The primary data source is utility bills, but other sources include

- Detailed printouts from time-of-use meters
- Combustion efficiency, eddy current, and water quality tests
- Recordings of temperature and relative humidity
- Submetered energy use data
- Data from building pressurization and depressurization
- Event recordings
- Occupancy schedules and group types
- Climatic data
- Data from similar buildings in similar climates
- Infrared scans
- Production records
- Computer modeling

Energy Accounting Process

The energy manager establishes procedures for meter reading, monitoring, and tabulating facility energy use and profiles. These tabulations indicate the cost of energy management efforts and the resulting energy cost avoidance. Also, the energy manager periodically reviews utility rates, rate structures, and trends as they affect the facility. Many utilities have free mailing lists for changes in their rate tariffs, which should be subscribed to by the energy manager. The energy manager provides periodic reports of energy management efforts to top management, summarizing the work accomplished, its cost-effectiveness, plans and suggested budget for future work, and projections of future utility costs. Utility bill analysis software can be used to track avoided costs. If energy conservation measures are to be cost-effective, continued monitoring and periodic re-auditing are necessary, because many energy conservation measures lose effectiveness if they are not carefully monitored and maintained. The procedures in ASHRAE *Guideline* 14 for determining energy savings can be used as energy accounting procedures to track changes in consumption and cost.

Energy Accounting

Energy accounting means tracking utility bills and consumption on a monthly basis to provide a current picture of building energy performance and to be able to identify trends and instances of excess use. An Internet search for "energy accounting" will produce Web sites for the major commercial providers of this software or service. In some cases the software is sold for installation on the user's computer; in other cases the program is Web-based and the user has a subscription enabling them to log on and enter data. For many users however, a simple spreadsheet is all that is needed.

Utility Rates

Because most energy management activities are dictated by economics, the energy manager must understand the utility rates that apply to each facility. Electric rates are usually more complex than gas or water rates and some rate structures can make cost calculations difficult. In addition to general commercial or institutional electric rates, special rates may exist such as time of day, interruptible service, on peak/off peak, summer/winter, and peak demand. Electric rate schedules vary widely in North America; Chapters 36 and 55 discuss these in detail. The energy manager should work with local utility companies to identify the most favorable utility rates and to understand how to qualify for them. The local utility representative can help the energy manager develop the most cost-effective methods of metering and billing. The energy manager must understand the utility rates, including the distinction between marginal and average costs and, in the case of demand-based elec-

tric rates, how demand is computed. See the Improving Discretionary Operations section in this chapter.

ANALYZING ENERGY DATA

Preparing for Cost and Efficiency Improvements

The first step in preparing for cost and efficiency improvements is understanding how energy is used. Opportunities for savings come in reducing (1) the cost per unit of energy, and then (2) energy consumption. Interest in energy efficiency rises when energy costs rise. It is very important to understand how a building's energy use relates to other similar facilities. If the energy budget is much higher than those for comparable facilities, there are likely to be many ways to reduce energy use cost-effectively. If the energy budget is much lower, there are likely to be fewer cost-effective opportunities.

Historically, energy users had little choice in selecting energy suppliers, and regulated tariffs applied based on certain customer use characteristics. In recent years, though, there has been a move in North America and other parts of the world toward deregulation of energy markets, and electricity and gas markets have much more flexibility in supply and pricing than in the past. Electric rate structures vary widely in North America; Chapter 36 discusses these in detail.

Electric utilities commonly meter both consumption and demand. **Demand** is the peak rate of consumption, typically integrated over a 15 or 30 min period. Electric utilities may also establish a ratchet billing procedure for demand. To fully understand the cost effect of the demand component of the utility bill, contact the local electric utility.

Some utilities use **real-time pricing (RTP)**, in which the utility calculates the marginal cost of power per hour for the next day, determines the price, and sends this hourly price (for the next day) to customers. The customer can then determine the amount of power to be consumed at different times of the day. More recently, a variation on RTP was introduced in some areas: **demand exchange and active load management** pays customers to shed loads during periods of high utility demand. Also called **demand reduction** or **demand response** programs, the utilities ask participating customers to reduce their demand for a period of time on as little as a few hours' notice.

There are many variations of billing methods, and it is important to understand the applicable rates. Caution is advised in designing or installing energy management and energy retrofit systems that take advantage of utility rate provisions, because these provisions can change. The structure or provisions of utility rates cannot be guaranteed for the life of the energy conservation opportunities. Some provisions that change include on-peak times, declining block rates, and demand ratchets. Chapter 55 has additional information on billing rates.

Analyzing Energy Use Data

Any reliable, applicable utility data should be examined. Utilities often provide metered use and demand data, often with measurement intervals as short as 15 min. Data from shorter time intervals are preferable to monthly data because anomalies are more apparent. High consumption at certain periods may reveal opportunities for cost reduction (Haberl and Komor 1990a, 1990b). If monthly data are used, they should be analyzed over several years.

A base year should be established as a reference point for future energy and energy cost reduction activities. In tabulating the data, the dates of meter readings should be recorded so that energy use can be normalized for differences in the number of days in a billing period. Any periods during which consumption was estimated rather than measured should be noted.

If energy data are available for more than one building and/or department under the energy manager's authority, each should be tabulated separately. Initial tabulations should include both energy and cost per unit area (in an industrial facility, this may be energy and cost per unit of goods produced). Document any information on variables that may have affected past energy use, such as heating or cooling degree-days, percent occupancy for a hotel, quantity of goods produced, building occupancy, hours of operation, or average daily weather conditions (see Chapter 28, Climatic Design Information, in the 2005 *ASHRAE Handbook—Fundamentals*).

Because these variables may not be directly proportional to energy use, it is best to plot information separately or to superimpose one plot over another, rather than developing units such as Btu per square foot per degree-day. As the data are tabulated, ongoing energy accounting procedures should be developed for consistent data collection and use in the future. Examples of ways to normalize energy consumption for temperature and other variations are provided in ASHRAE *Guideline* 14.

Potential savings areas can be identified by breaking down a facility's energy consumption into base and weather-dependent energy consumption. **Base energy consumption** is the amount of energy consumed independent of weather, such as for lighting, motors, domestic hot water, and miscellaneous office equipment. **Weather-dependent energy consumption** includes energy consumed by equipment such as chillers and boilers.

Identifying the base and weather-dependent energy consumption identifies areas where the greatest savings potential exists. For example, if energy used for cooling is only 10% of total electrical consumption, then savings generated from a chilled-water reset strategy are likely to be small.

Base load energy use is the amount of energy consumed independent of weather. When a building has electric cooling and no electric heating, the base load energy use is normally the energy consumed during the winter. The opposite is true for heating. The annual estimated base load energy consumption can be obtained by establishing the average monthly consumption during nonheating or noncooling months and multiplying by 12. For many buildings, subtracting the base load energy consumption from the total annual energy consumption yields an accurate estimate of heating or cooling energy consumption. This approach is not valid when building use differs from summer to winter; when cooling operates year-round; or when space heating is used during summer, as for reheat. In many cases, base load energy use analysis can be improved by using hourly load data, which may be available from the utility company. **Electric load factors (ELFs)** and occupancy factors can also be used instead of hourly energy profiles (Haberl and Komor 1990a, 1990b).

Although it can be difficult to relate heating and cooling energy used in commercial buildings directly to the severity of the weather, several authors, including Fels (1986) and Spielvogel (1984), suggest that this is possible using a curve-fitting method to calculate the balance point of a building (discussed in Chapter 32 of the 2005 *ASHRAE Handbook—Fundamentals*). Pitfalls of such an analysis are (1) estimated rather than actual utility use data are used; (2) the actual dates of the metered information must be used, together with average billing period weather data; and (3) building use and/or operation are not regular.

More detailed breakdown of energy use requires that some metered data be collected daily (winter versus summer days, weekdays versus weekends) and that some hourly information be collected to develop profiles for night (unoccupied), morning warm-up, day (occupied), and shutdown. (Submetering is assumed to not be installed in the building.) Individual metering of various energy end uses provides the energy manager with information to apply energy management principles optimally. For more information, see Chapter 40.

An example spreadsheet using three years of electricity bill data for a two-story office building in Atlanta, Georgia, is presented in Table 1. (See Chapter 30 of the 2005 *ASHRAE Handbook—Fundamentals* for floor plans and elevations of the building.)

Table 1 Electricity Consumption for Atlanta Example Building

| | | Occupancy Factor | 38.1% | | Building Area: 30,700 ft^2 | | | | | | |
| | | Summer ELF 2002 | 87.3% | Summer ELF 2003 | 37.4% | Summer ELF 2004 | 54.7% | | | | |

Year	Month	Bill Start	Bill End	Billing Period	Billed Use, kWh	Actual Demand, kW	Billed Demand, kW	LF	Daily Use, kWh	Daily Base Use, kWh	Monthly Base Use, kWh	Percent Excess Use, kWh
2002	Jan-02	1/2/2002	1/31/2002	29	54,600	166	166	47.3%	1883	1665	48,285	11.6%
2002	Feb-02	1/31/2002	2/28/2002	28	46,620	148	166	46.9%	1665[a]	1665	46,620	0.0%
2002	Mar-02	2/28/2002	4/1/2002	32	60,900	140[b,c]	166	56.6%	1903	1665	53,280	12.5%
2002	Apr-02	4/1/2002	4/29/2002	28	56,340	166	166	50.5%	2012	1665	46,620	17.3%
2002	May-02	4/29/2002	5/31/2002	32	65,520	159	166	53.7%	2048	1665	53,280	18.7%
2002	Jun-02	5/31/2002	6/28/2002	28	63,540	180	180	52.5%	2269	1665	46,620	26.6%
2002	Jul-02	6/28/2002	7/31/2002	33	76,860	158	171	61.4%	2329	1665	54,945	28.5%
2002	Aug-02	7/31/2002	8/30/2002	30	82,620	192	192	59.8%	2754[a]	1665	49,950	39.5%
2002	Sep-02	8/30/2002	9/30/2002	31	66,780	195[b]	195[b]	46.0%	2154	1665	51,615	22.7%
2002	Oct-02	9/30/2002	10/29/2002	29	60,720	193	185	45.2%	2094	1665	48,285	20.5%
2002	Nov-02	10/29/2002	12/2/2002	34	62,100	151	185	50.4%	1826	1665	56,610	8.8%
2002	Dec-02	12/2/2002	1/2/2003	31	60,180	166	185	48.7%	1941	1665	51,615	14.2%
2003	Jan-03	1/2/2003	1/31/2003	29	57,120	178	185	46.1%	1970	1704	49,429	13.5%
2003	Feb-03	1/31/2003	3/3/2003	31	61,920	145	185	57.4%	1997	1704	52,838	14.7%
2003	Mar-03	3/3/2003	4/1/2003	29	60,060	140	185	61.6%	2071	1704	49,429	17.7%
2003	Apr-03	4/1/2003	4/30/2003	29	62,640	154	185	58.4%	2160	1704	49,429	21.1%
2003	May-03	4/30/2003	6/2/2003	33	73,440	161	185	57.6%	2225[a]	1704	56,247	23.4%
2003	Jun-03	6/2/2003	6/28/2003	26	53,100	171	185	49.8%	2042	1704	44,316	16.5%
2003	Jul-03	6/28/2003	7/30/2003	32	67,320	180[b]	185[b]	48.7%	2104	1704	54,542	19.0%
2003	Aug-03	7/30/2003	8/29/2003	30	66,000	170	185	53.9%	2200	1704	51,133	22.5%
2003	Sep-03	8/29/2003	9/30/2003	32	63,960	149	171	55.9%	1999	1704	54,542	14.7%
2003	Oct-03	9/30/2003	10/30/2003	30	55,260	122	171	62.9%	1842	1704	51,133	7.5%
2003	Nov-03	10/30/2003	11/26/2003	27	46,020	140	171	50.7%	1704[a]	1704	46,020	0.0%
2003	Dec-03	11/26/2003	12/30/2003	34	61,260	141	171	53.2%	1802	1704	57,951	5.4%
2004	Jan-04	12/30/2003	1/30/2004	31	59,040	145	171	54.7%	1905	1676	51,960	12.0%
2004	Feb-04	1/30/2004	2/28/2004	29	54,240	159	171	49.0%	1870	1676	48,608	10.4%
2004	Mar-04	2/28/2004	3/19/2004	20	37,080	122	171	63.3%	1854	1676	33,523	9.6%
2004	Apr-04	3/19/2004	3/31/2004	12	22,140	133	171	57.8%	1845	1676	20,114	9.2%
2004	May-04	3/31/2004	5/4/2004	34	64,260	148	171	53.2%	1890	1676	56,988	11.3%
2004	Jun-04	5/4/2004	6/2/2004	29	63,720	148	171	61.9%	2197	1676	48,608	23.7%
2004	Jul-04	6/2/2004	7/2/2004	30	69,120	169	169	56.8%	2304	1676	50,284	27.3%
2004	Aug-04	7/2/2004	8/3/2004	32	73,800	170[b]	170[b]	56.5%	2306[a]	1676	53,636	27.3%
2004	Sep-04	8/3/2004	9/1/2004	29	64,500	166[b]	166[b]	55.8%	2224	1676	48,608	24.6%
2004	Oct-04	9/1/2004	10/1/2004	30	60,060	152	161	54.9%	2002	1676	50,284	16.3%
2004	Nov-04	10/1/2004	11/2/2004	32	65,760	128	161	66.9%	2055	1676	53,636	18.4%
2004	Dec-04	11/2/2004	12/3/2004	31	51,960	132	161	52.9%	1676[a]	1676	51,960	0.0%

	kWh·y/ft^2			Days	Total kWh	Peak kW	Billed kW	Avg LF	Daily Base Use, kWh	Total Base Use, kWh
2002	24.65			365	756,780	195	195	51.6%	1665	607,725
2003	23.72			362	728,100	180	185	51.5%	1704	617,009
2004	22.33			339	685,680	170	171	52.4%	1676	568,208

[a]Maximum or minimum value for year.   [b]Peak demand for year.   [c]Minimum demand used in seasonal ELF calculation.

Electrical Use Profile

The **electrical use profile (EUP)** report, shown in Figure 2, divides electrical consumption into base and weather-dependent consumption to help identify where the greatest potential exists to save electricity. The average daily consumption for each month appears in the Daily Use column in Table 1, and is plotted in the EUP graph. The average daily consumption is calculated by dividing the consumption for a particular month by its billing days.

The lowest value in the Daily Use column is used to plot the facility's base electrical consumption (shown as the Base Use line) in Figure 2. Where a facility uses electricity only for cooling or heating, or in an all-electric facility where there is no overlap between cooling and heating, the difference between these two lines represents the weather-dependent electrical consumption.
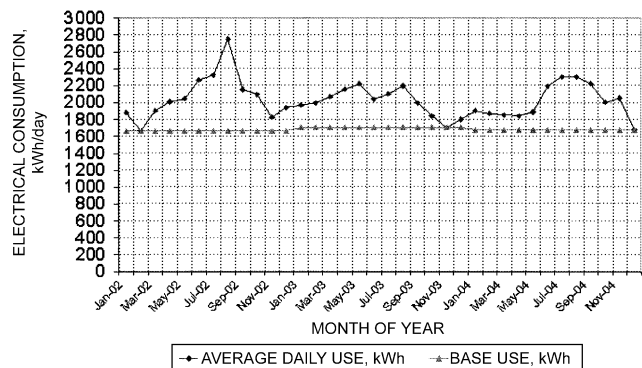
Fig. 2 Electrical Use Profile for Atlanta Example Building

Weather-dependent energy consumption (either electric or other fuels) may then be compared to the **cooling degree-days (CDD)** or **heating degree-days (HDD)** totals for the same time period. This comparison shows how the building performs from month to month or year to year. The HDDs stop and CDDs start at an outdoor temperature called the balance point, which is defined as that value of the outdoor temperature at which, for the specified value of the interior temperature, the total heat loss is equal to the heat gain from the sun, occupants, lights, etc. Use caution when determining daily base use in all-electric buildings, because some have periods of overlap with their heating and cooling systems. In these cases, using this example, the base load is somewhat overestimated, causing the heating and cooling energy consumption estimates to be conservative.

Examine the Average Daily Use line to see if it follows the expected seasonal curve. For example, the shoulders of the curve for an electrically cooled, gas-heated hospital should closely follow the base electrical use line in the winter. As summer approaches, this curve should rise steadily to reflect the increased cooling load. Any errors in meter readings, reading dates, or consumption variances should show up as unusual peaks or valleys. Reexamine the associated data and correct errors as necessary.

If an unusual profile remains after correcting any errors (or after discovering that no errors were made in the data entry), an area of potential energy savings may be identified. For example, if the Average Daily Use line for the facility is running near summer levels during March, April, May, October, and November, simultaneous heating and cooling may be occurring. This situation is illustrated in Figure 2, and often occurs with dual-duct systems.

This simultaneous heating and cooling is also indicated by the values in the Percent Excess Use column of Table 1, which shows the percent difference between the monthly base consumption value appearing in the Monthly Base Use column and the billed consumption for the month. In Figure 2, note how the excess consumption for spring and fall months runs close to the summer percentages.

The monthly base consumption is calculated by multiplying the lowest value from the Daily Use column by the number of billing days for each month.

For electrically cooled, gas-heated facilities, weather-dependent consumption is the difference between the totals of the Monthly Base Use column and the Billed Use column.

For an all-electric facility, subtract the total monthly consumption from total billed use for the cooling months, then do the same calculations for heating months to determine the electric cooling and heating loads, respectively.

Calculating Electrical Load and Occupancy Factors

Another method for detecting potential energy savings is to compare the facility's electrical load factor to its occupancy factor. An ELF exceeding its occupancy factor indicates a higher than expected electrical rate of consumption occurring past the normal occupancy of the building (e.g., lights or fans are left on after occupied hours, or, for an electrically cooled building, that air conditioning is not shut off as early in the day as possible during summer. Direct digital control (DDC) control strategies, time-of-day scheduling, and lighting controls are several ECMs addressing these concerns.

The ELF is the ratio between the average daily use and the maximum possible use if peak demand operated for a 24 h period. The occupancy factor is the ratio between the hours a building actually is occupied and the maximum possible occupied hours (i.e., if the building were occupied 24 h a day).

To calculate the ELF, find the month with the lowest demand on the utility data analysis spreadsheet. This value represents the base monthly peak demand, and is usually found in the same or adjacent month as the month with the lowest consumption. From the EUP report, find the lowest value in the Daily Use column. For example,

the lowest average daily use for the office building in Table 1 is 1704 kWh (in November 2003), and the lowest monthly demand from the spreadsheet is 122 kW (in October 2003). The ELF is calculated as follows:

$$ ELF = \frac{\text{Lowest average daily use}}{\text{Lowest monthly demand} \times 24} = \frac{1704}{122 \times 24} = 58\% $$

The office is normally occupied from 7:30 AM to 6:30 PM, Monday to Friday. Therefore, the occupancy factor is calculated as

$$ \frac{\text{Occupancy}}{\text{factor}} = \frac{\text{Actual weekly occupied hours}}{24 \text{ h} \times 7 \text{ days}} = \frac{55}{168} = 33\% $$

Calculating Seasonal ELFs

When applicable, ELFs can also be calculated for cooling and heating seasons. Typical defaults are May to August as cooling months, and the rest of the year as heating months, but these change based on geographic location.

The steps for calculating a seasonal ELF are as follows:

1. The daily base consumption is determined by values appearing in the Daily Use column of the EUP report. Subtract the lowest value (regardless of season) from the highest (peak) value of the appropriate season in this column.
2. The base demand is determined by values appearing on the spreadsheet. Subtract the lowest monthly demand for the year from the demand recorded for the month with the highest average daily use. These calculations can be refined further if on- and off-peak data are entered into the spreadsheet.

For example, because the electrically cooled Atlanta example building operates year-round, the summer ELF must also be calculated. The daily base consumption (1089) is determined by subtracting the lowest value (1665) from the highest cooling-season value (2754) in the Daily Use column of the EUP report.

From the spreadsheet, take the demand from September 2002 (the month with the peak cooling-season actual demand) and subtract the lowest monthly demand from the spreadsheet (195 – 140) to determine the cooling-season base demand (55). Thus, the summer ELF is

$$ \text{Summer ELF} = \frac{1089}{55 \times 24} = 82\% \text{ (for 2002)} $$

These calculations show that the cooling equipment is operating beyond building occupancy (82% versus 33%) Therefore, savings from energy conservation measures (ECMs) for lights, fans, and cooling equipment run times should be investigated. Note that comparing the ELF to the occupancy factor is meaningless for buildings occupied 24 h a day, such as a hospital.

Similar tables and charts may be created for natural gas, water, and other utilities through an energy management program.

Electric Demand Billing

For the Atlanta example building, the demand rate is of the ratchet type (see Chapter 55) and billed demand is determined as a percentage of actual demand in the summer months. How the ratchet operates is illustrated in Figure 3. In this example, billed demand is the greater of the measured demand or 95% of the highest measured demand within the past 12 months. For example, the billed demand for January 2004 was 171 kW (171 = 0.95 × 180), or 95% of the actual demand from July 2003. Currently, most commercial buildings are not subject to this type of demand billing structure, but in some regions it is a common practice for electric utilities.

In Table 1, the actual demand in the first six months of 2003 had no effect on the billed demand, and therefore no effect on the dollar

95% OF HIGHEST SUMMER DEMAND DETERMINES BILLED DEMAND FOR CURRENT AND PAST 11 MONTHS

	Jan-02	Feb-02	Mar-02	Apr-02	May-02	Jun-02	Jul-02	Aug-02	Sep-02	Oct-02	Nov-02	Dec-02	Jan-03	Feb-03	Mar-03	Apr-03	May-03	Jun-03	Jul-03	Aug-03	Sep-03	Oct-03	Nov-03	Dec-03	Jan-04	Feb-04	Mar-04	Apr-04	May-04	Jun-04	Jul-04	Aug-04	Sep-04	Oct-04	Nov-04	Dec-04
■ Actual KW	166	148	140	166	159	180	158	192	195	193	151	166	178	145	140	154	161	171	180	170	149	122	140	141	145	159	122	133	148	148	169	170	166	152	128	132
□ Billed kW	166	166	166	166	166	180	171	192	195	185	185	185	185	185	185	185	185	185	185	185	171	171	171	171	171	171	171	171	171	171	169	170	166	161	161	161

Fig. 3   Comparison Between Actual and Billed Demand for Atlanta Example Building

amount of the bill; the same is true for the last three months of the year. Because of the demand ratchet, the billed demand in January 2004 (171 kW) was set in July 2003. This means that any conservation measures that reduce peak demand will not affect billed demand until the following summer (e.g., June to September 2004); however, consumption savings begin at the next billing cycle. The effect of demand ratchet rates is that any conservation measures implemented have a longer initial payback period simply because of the utility rate structure. This means that the energy manager should also investigate whether the facility can purchase electricity using a different rate structure, such as a time-of-use (TOU) or seasonal rate. Most smaller facilities are not billed based on their peak demand requirements.

Benchmarking Energy Use

To determine whether a building or industrial process is a good candidate for energy efficiency improvements, **benchmarking** (comparing a building's normalized energy consumption to that of other buildings) can be a useful first measure of energy efficiency. The most used normalization factor is the gross floor area of a building (energy use per unit area). Benchmarking is less accurate than an audit or engineering analysis, but can provide a good overall picture of relative energy use for a given facility, and is an important first step to understanding energy use and savings potential. Relative energy use is commonly expressed in energy utilization index (EUI; energy use per unit area per year) and cost utilization index (CUI; energy cost per unit area per year). The Atlanta example building is 30,700 ft^2 in size, so its 2004 EUI is 76,200 Btu/ft^2 and its CUI is $1.47/$ft^2$. Natural gas use, or use of any other fuels, are generally added to total energy use and costs to calculate EUI and CUI. Because the building is all-electric, though, no other fuels need be considered for it.

Databases. Compiling a database of past energy use and cost is important in developing an energy management program. All applicable, reliable utility data should be examined. ASHRAE *Standard* 105 contains information that allows uniform, consistent expressions of energy consumption in both proposed and existing buildings.

Comparing a building's energy use with that of comparable buildings in the same region is a good way to check its relative efficiency. Two sources of benchmarking data for U.S. buildings are ENERGY STAR® (www.energystar.gov) and the U.S. Department of Energy's Energy Information Administration (DOE/EIA). Data on U.S. buildings in all sectors are summarized in periodic reports by the DOE/EIA. Tables 2 to 4 present DOE/ EIA CBECS data in a combined format. Table 2 lists EUI input data and EUI distributions for the buildings surveyed in 2003. Table 3 lists the 2003 *Commercial Buildings Energy Consumption Survey* (CBECS) electricity per unit of floor area, and Table 4 shows CUI distributions. Tables 5 and 6 present data from the 1997 *Residential Energy Consumption Survey* (RECS). Table 5 provides population breakouts by fuel type and end uses, and Table 6 gives breakouts by specific characteristics of homes. More complete and up-to-date information on the CBECS is available at www.eia.doe.gov/emeu/cbecs, and on the RECS at www.eia.doe.gov/emeu/recs. When referring to these tables, keep in mind the operating or occupied hours of the specific facility and the current utility rates.

When an energy management program for a new building is established, the energy use database may consist solely of typical data for similar buildings, as in Table 2. This may be supplemented by energy simulation data for the specific building, if such data were developed during design. In addition, a new building and its systems should be properly commissioned on completion of construction to ensure proper operation of all systems, including any energy conservation features (see ASHRAE *Guideline* 1 and Chapter 42).

All the data presented in these tables are derived from detailed reports of consumption patterns in buildings. Before using them, however, it is important to understand how they were derived. For example, all household energy consumption data in Table 6 are averages, and may not reflect variations in appliances or fuel selections

Table 2　2003 Commercial Sector Floor Area and EUI Percentiles

Building Use	Calculated, Weighted		Actual Number of Buildings, N	Calculated, Weighted Energy Use Index (EUI) Values Site Energy, kBtu/yr per gross square foot					
	Number of Buildings, Hundreds	Floor Area, 10^9 ft^2		Percentiles					Mean
				10th	25th	50th	75th	90th	
Administrative/professional office	442	6.63	555	28.1	41	62	93	138	75
Bank/other financial	104	1.10	75	55.7	67	87	117	184	106
Clinic/other outpatient health	66	0.75	100	28.7	41	66	97	175	84
College/university	34	1.42	88	14.1	67	108	178	215	122
Convenience store	57	0.16	28	68.6	156	232	352	415	274
Convenience store with gas station	72	0.28	32	82.2	135	211	278	409	225
Distribution/shipping center	155	5.25	231	8.7	17	33	54	91	45
Dormitory/fraternity/sorority	16	0.51	37	36.3	65	74	100	154	90
Elementary/middle school	177	4.75	331	21.1	35	54	93	127	76
Entertainment/culture	27	0.50	50	1.7	29	46	134	418	95
Fast food	78	0.26	95	176.3	268	418	816	933	534
Fire station/police station	53	0.38	47	6.9	24	82	112	137	78
Government office	84	1.55	150	31.5	52	77	103	149	85
Grocery store/food market	86	0.71	117	98.1	138	185	239	437	213
High school	68	2.52	126	19.8	44	65	99	130	75
Hospital/inpatient health	8	1.90	217	108.1	169	196	279	355	227
Hotel	20	1.90	86	39.7	51	73	116	183	95
Laboratory	9	0.65	43	98.0	165	270	505	925	362
Library	20	0.56	36	35.0	67	92	121	197	104
Medical office (diagnostic)	54	0.50	58	14.1	25	44	100	137	60
Medical office (nondiagnostic)	37	0.22	33	25.7	40	52	66	109	59
Mixed-use office	84	2.30	172	20.0	38	71	106	158	88
Motel or inn	70	1.05	109	23.9	37	67	102	197	87
Nonrefrigerated warehouse	229	3.05	172	2.3	6	19	46	87	34
Nursing home/assisted living	22	0.98	73	41.6	77	116	184	205	124
Other	70	1.08	68	5.5	29	69	96	118	74
Other classroom education	51	0.71	60	4.3	23	40	64	108	51
Other food sales	10	0.10	10	31.5	37	58	190	343	126
Other food service	58	0.33	56	39.6	71	125	309	548	242
Other lodging	16	0.65	28	31.2	54	71	83	146	76
Other office	73	0.41	52	15.3	41	57	84	146	69
Other public assembly	32	0.42	31	9.9	30	42	73	155	65
Other public order and safety	17	0.71	38	44.0	58	93	160	308	127
Other retail	47	0.24	42	32.7	65	92	146	205	120
Other service	139	0.48	171	28.0	50	86	164	303	168
Post office/postal center	19	0.50	23	7.2	58	64	76	97	64
Preschool/daycare	56	0.48	46	18.8	35	59	112	121	75
Recreation	96	1.28	99	13.4	24	40	88	152	68
Refrigerated warehouse	15	0.53	20	6.5	13	143	190	257	127
Religious worship	370	3.75	313	9.3	17	33	63	88	46
Repair shop	76	0.65	51	7.0	13	30	54	72	37
Restaurant/cafeteria	161	1.06	212	51.8	117	207	462	635	302
Retail store	347	3.48	460	14.2	25	45	93	170	72
Self-storage	198	1.26	84	2.1	4	7	10	15	9
Social/meeting	101	1.18	78	7.9	15	41	71	93	52
Vacant	182	2.57	178	1.4	3	12	31	77	26
Vehicle dealership/showroom	50	0.60	40	24.5	40	82	110	248	110
Vehicle service/repair shop	212	1.21	131	10.1	16	37	86	137	58
Vehicle storage/maintenance	176	1.21	99	0.9	4	21	53	152	54
SUM or Mean for sector	4645	64.78	5451	9.8	26	56	108	207	97

Source: Calculated based on DOE/EIA preliminary 2003 CBECS microdata.

for different buildings. Therefore, when using the data, verify correct use with the original EIA documents.

Mazzucchi (1992) lists data elements useful for normalizing and comparing utility billing information. Metered energy consumption and cost data are also gathered and published by building owners' trade associations, such as the Building Owners and Managers Association International (BOMA), the National Restaurant Association (NRA), and the American Hotel and Lodging Association (AH&LA).

The quality of published energy consumption data for buildings varies because the data are collected for different purposes by people with different levels of technical knowledge of buildings. The data presented here are primarily national. In some cases, local energy consumption data may be available from local utility companies or state or provincial energy offices.

Additional energy use information for homes and commercial buildings in Canada can be found at the Office of Energy Efficiency

Table 3   Electricity Index Percentiles from 2003 Commercial Survey

| Building Use | Weighted Electricity Use Index Values, kWh/yr per gross square foot | | | | | |
| | Percentiles | | | | | |
	10th	25th	50th	75th	90th	Mean
Administrative/professional office	3.54	6.7	11.0	15.0	24.1	12.7
Bank/other financial	6.23	14.5	22.2	29.5	33.3	22.5
Clinic/other outpatient health	4.94	9.4	15.2	20.7	27.3	16.6
College/university	4.13	10.5	15.0	24.0	42.3	17.7
Convenience store	20.09	43.3	65.3	78.7	107.4	69.6
Convenience store with gas station	24.09	37.7	48.1	79.0	120.0	62.0
Distribution/shipping center	1.77	2.9	4.5	7.4	9.9	5.7
Dormitory/fraternity/sorority	2.16	3.3	5.1	6.6	16.6	6.7
Elementary/middle school	3.45	5.7	9.3	14.0	19.7	12.1
Entertainment/culture	0.49	1.0	7.4	16.9	122.5	20.9
Fast food	27.97	48.0	81.8	131.2	168.1	95.5
Fire station/police station	1.14	3.8	6.6	12.6	22.0	9.8
Government office	3.96	8.1	10.8	19.3	26.0	14.3
Grocery store/food market	26.12	32.2	42.4	54.4	100.6	51.7
High school	3.50	4.5	7.5	12.8	19.3	9.7
Hospital/inpatient health	15.24	21.8	24.0	35.6	45.9	28.7
Hotel	6.73	11.6	14.3	18.3	27.4	16.4
Laboratory	11.43	25.5	39.2	54.6	95.6	44.1
Library	6.34	8.7	15.5	23.2	34.3	17.3
Medical office (diagnostic)	2.21	4.1	7.6	13.8	18.3	9.6
Medical office (nondiagnostic)	2.41	4.5	7.4	12.1	15.3	8.6
Mixed-use office	3.40	5.5	11.1	18.0	28.9	14.3
Motel or inn	4.95	7.5	10.8	18.1	26.3	13.6
Nonrefrigerated warehouse	0.38	1.0	2.9	5.9	10.7	5.4
Nursing home/assisted living	6.33	8.1	14.9	21.0	25.9	15.9
Other	1.60	3.0	5.8	12.2	24.7	9.5
Other classroom education	1.27	2.8	4.9	9.2	15.7	6.6
Other food sales	9.22	9.2	10.8	12.6	58.5	22.0
Other food service	8.85	15.4	27.2	60.1	89.5	40.3
Other lodging	2.86	3.7	14.0	21.0	22.7	12.0
Other office	3.04	4.5	9.4	16.2	18.3	10.8
Other public assembly	1.13	2.6	3.4	12.3	13.8	7.5
Other public order and safety	5.45	14.4	16.7	20.7	42.1	18.9
Other retail	4.87	6.7	22.4	27.2	38.3	19.8
Other service	4.13	7.5	13.4	19.6	28.6	16.3
Post office/postal center	2.10	3.2	7.2	13.3	21.3	9.9
Preschool/daycare	3.34	5.5	8.8	12.1	28.9	11.6
Recreation	1.59	2.9	5.1	10.8	19.3	8.8
Refrigerated warehouse	1.89	3.8	35.2	51.1	55.7	28.5
Religious worship	1.06	1.9	3.5	6.0	8.6	4.5
Repair shop	1.88	2.6	6.1	7.6	14.2	6.8
Restaurant/cafeteria	9.76	15.2	28.7	49.9	88.2	37.9
Retail store	2.41	3.9	8.1	15.2	27.3	12.5
Self-storage	0.63	1.2	2.1	2.8	3.8	2.2
Social/meeting	1.01	1.8	2.9	7.5	12.8	6.2
Vacant	0.29	0.4	1.7	3.8	7.8	3.2
Vehicle dealership/showroom	2.50	7.2	13.8	21.9	33.9	15.7
Vehicle service/repair shop	1.96	3.3	5.6	9.8	18.6	8.2
Vehicle storage/maintenance	0.27	1.2	3.3	6.4	10.4	5.2
SUM or Mean for sector	1.59	3.6	8.3	17.1	35.4	15.7

Source: Calculated based on DOE/EIA preliminary 2003 CBECS microdata.

at http://www.oee.nrcan.gc.ca/corporate/statistics/neud/dpa/data_e/publications.cfm.

SURVEYS AND AUDITS

This section provides guidance on preparing for and conducting building surveys and describes the levels of intensity for investigating ECM opportunities in a building.

Energy Audits

The objectives of an energy analysis or audit are to identify and develop modifications to reduce energy use and/or cost of operating a building. The results should be presented in a format that provides the information needed by an owner/operator to decide if any, some,

or all of the recommended modifications should be implemented. Energy audits include some or all of the following:

1. Collect and analyze historical energy use
   - Review more than one year of energy bills (preferably three years)
   - Review billing rate class options with utility
   - Review monthly patterns for irregularities
   - Compare the building's EUI with publicly available indices of similar buildings
   - Derive target goals for energy, demand, and cost indices for a building with similar characteristics
2. Study the building and its operational characteristics
   - Acquire a basic understanding of the mechanical and electrical operating systems

Table 4 Energy Cost Percentiles from 2003 Commercial Survey

	Weighted Energy Cost Values, $/yr per gross square foot					
	Percentiles					
Building Use	10th	25th	50th	75th	90th	Mean
Administrative/professional office	0.50	0.82	1.36	1.92	2.58	1.55
Bank/other financial	1.09	1.37	2.00	2.93	4.47	2.41
Clinic/other outpatient health	0.61	0.87	1.53	2.03	4.13	1.74
College/university	0.44	1.20	1.37	2.27	$3.01	1.82
Convenience store	2.48	3.75	5.26	8.02	10.12	6.17
Convenience store with gas station	1.99	2.75	4.61	6.83	8.74	5.12
Distribution/shipping center	0.24	0.33	0.54	0.88	1.37	0.74
Dormitory/fraternity/sorority	0.58	0.69	0.87	1.29	2.13	1.07
Elementary/middle school	0.54	0.78	1.09	1.57	2.60	1.48
Entertainment/culture	0.14	0.42	0.56	2.25	17.82	2.83
Fast food	2.93	4.98	8.87	12.29	14.14	8.92
Fire station/police station	0.10	0.53	1.15	1.73	2.83	1.31
Government office	0.52	0.90	1.40	1.88	2.66	1.52
Grocery store/food market	2.60	3.07	4.31	5.27	6.85	4.84
High school	0.60	0.87	1.02	1.60	2.19	1.30
Hospital/inpatient health	1.37	2.16	2.46	3.17	3.55	2.70
Hotel	0.74	1.05	1.33	1.76	2.52	1.58
Laboratory	1.34	3.09	4.52	7.64	10.81	5.18
Library	0.78	1.06	1.37	2.41	2.92	1.68
Medical office (diagnostic)	0.33	0.68	1.02	2.13	2.53	1.33
Medical office (nondiagnostic)	0.58	0.79	1.06	1.44	1.92	1.15
Mixed-use office	0.46	0.85	1.30	1.96	2.90	1.78
Motel or inn	0.49	0.83	1.21	1.82	2.67	1.48
Nonrefrigerated warehouse	0.06	0.17	0.38	0.80	1.43	0.61
Nursing home/assisted living	0.73	1.12	1.52	2.47	2.99	1.78
Other	0.15	0.51	0.93	1.81	2.41	1.35
Other classroom education	0.21	0.50	0.92	1.26	2.14	0.96
Other food sales	0.60	0.72	0.95	2.35	6.02	2.20
Other food service	0.79	1.60	2.44	6.50	11.56	4.72
Other lodging	0.55	0.56	1.13	1.71	2.76	1.30
Other office	0.37	0.71	1.19	2.16	2.56	1.47
Other public assembly	0.35	0.50	0.81	1.56	2.06	1.15
Other public order and safety	1.00	1.13	1.56	3.38	4.74	2.06
Other retail	0.97	1.19	1.59	2.98	5.60	2.43
Other service	0.76	1.13	1.58	2.92	7.29	2.71
Post office/postal center	0.32	0.78	1.09	1.44	1.89	1.07
Preschool/daycare	0.46	0.77	1.09	1.57	2.63	1.30
Recreation	0.30	0.53	0.87	1.38	2.33	1.14
Refrigerated warehouse	0.38	0.38	2.21	4.00	5.25	2.45
Religious worship	0.25	0.37	0.60	0.84	1.32	0.72
Repair shop	0.20	0.35	0.61	1.15	1.47	0.75
Restaurant/cafeteria	1.12	1.86	3.33	7.44	10.48	4.80
Retail store	0.36	0.53	0.98	1.77	2.90	1.38
Self-storage	0.05	0.10	0.20	0.27	0.52	0.23
Social/meeting	0.19	0.33	0.66	1.02	2.27	0.89
Vacant	0.04	0.08	0.27	0.70	1.19	0.48
Vehicle dealership/showroom	0.67	0.89	1.37	2.97	3.98	2.07
Vehicle service/repair shop	0.29	0.50	0.77	1.38	2.07	1.10
Vehicle storage/maintenance	0.04	0.16	0.48	1.12	1.96	0.83
SUM or Mean for sector	0.26	0.54	1.06	2.00	3.93	1.80

Source: Calculated based on DOE/EIA preliminary 2003 CBECS microdata.

- Perform a walk-through survey of the facility to become familiar with its construction, equipment, operation, and maintenance
- Meet with owner/operator and occupants to learn of special problems or needs of the facility
- Identify any required repairs to existing systems and equipment

3. Identify potential modifications to reduce energy use and/or cost

- Identify low-cost/no-cost changes to the facility or to operating and maintenance procedures
- Identify potential equipment retrofit opportunities
- Outline effect on occupant service requirements
- Identify any training required for operating staff to maintain measures
- Perform a rough estimate to determine the approximate breakdown of energy use for significant end-use categories

Table 5 1997 Residential Annual End-Use Consumption

Energy Source and End Use/Appliance	Households, 10^6	Usage per Household
Electricity, total	101.4	10,219 kWh
Space heating	42.0	2,807 kWh
Air conditioning	72.6	1,677 kWh
Water heating	40.2	2,835 kWh
Appliances	101.4	6,733 kWh
Natural Gas, total	61.9	83×10^3 ft^3
Space heating	54.5	65×10^3 ft^3
Water heating	52.8	24×10^3 ft^3
Appliances	40.4	9×10^3 ft^3
Fuel Oil, total	10.0	730 gal
Space heating	9.8	625 gal
Water heating	5.2	219 gal
LPG, total	8.1	488 gal
Space heating	5.6	502 gal
Water heating	3.3	258 gal
Appliances	4.8	55 gal
Kerosene, total, space heating	3.5	126 gal

Source: www.eia.doe.gov/emeu/recs/recs97 Fuel Tables 1 to 5.

4. Perform an engineering and economic analysis of potential modifications
   - For each practical measure, determine resultant savings
   - Estimate effects on building operations and maintenance costs
   - Review effect on nonenergy operating costs
   - Prepare a financial evaluation of estimated total potential investment using appropriate techniques and criteria
5. Prepare a rank-ordered list of appropriate modifications
   - List all possible energy savings modifications
   - Select those that may be considered practical by the building owner
   - Assume that modifications with highest operational priority and/or best return on investment will be implemented first
   - Provide preliminary implementation costs and savings estimates
6. Prepare a report to document analysis process and results
   - Provide description of building and its requirements, and an inventory of major energy-using equipment
   - Clearly state savings from each modification and assumptions on which each is based
   - Discuss existing situation and why it is using excess energy
   - Review list of practical modifications with the owner, and select those to be pursued
   - Prioritize modifications in order of implementation
   - If necessary, recommend measurement and verification methods to determine effectiveness of measures implemented

Three levels of energy audits or analysis have been defined (Mazzucchi 1992). Depending on the physical and energy use characteristics of a building and the owner's needs and resources, one or more of the three different levels of effort can be used.

Level I: Walk-Through Assessment. This involves assessing a building's energy cost and efficiency by analyzing energy bills and briefly surveying the building, accompanied by the building operator. Level I analysis identifies and provides a savings and cost analysis of low-cost/no-cost measures. It also lists potential capital improvements that merit further consideration, along with an initial judgment of potential costs and savings. The level of detail depends on the experience of the auditor or on the client's specifications.

The Level I audit is most applicable when there is some doubt about the energy savings potential of a building, or when an owner wishes to establish which buildings in a complex have the greatest potential for energy savings. The results can be used to develop a priority list for buildings that are recommended for a Level II or III audit.

Level II: Energy Survey and Analysis. This includes a more detailed building survey and energy analysis. A breakdown of energy use in the building is provided. Level II analysis identifies and provides the savings and cost analysis of all practical measures that meet the owner's constraints and economic criteria, along with a discussion of any effect on operation and maintenance procedures. It also lists potential capital-intensive improvements that require more thorough data collection and analysis, along with an initial judgment of potential costs and savings. This level of analysis is adequate for most buildings and measures.

Level III: Detailed Analysis of Capital-Intensive Modifications. This focuses on potential capital-intensive projects identified during Level II and involves more detailed field data gathering and engineering analysis. It provides detailed project cost and savings information with a level of confidence high enough for major capital investment decisions.

The levels of energy audits do not have sharp boundaries. They are general categories for identifying the type of information that can be expected and an indication of the level of confidence in the results; that is, various measures may be subjected to different levels of analysis during energy analysis of a particular building. In the complete development of energy management program, Level II audits should be performed on all facilities, although Level I audits are useful in establishing the program. The collected data are used to calculate an energy use profile that includes all end-use categories. From the energy use profiles, it is possible to develop and evaluate energy conservation opportunities.

In conducting an energy audit, a thorough systems approach produces the best results. This approach has been described as starting at the end rather than at the beginning. For example, consider a factory with steam boilers in constant operation. An expedient (and often cost-effective) approach is to measure the combustion efficiency of each boiler and to improve boiler efficiency. Beginning at the end requires finding all or most of the end uses of steam in the plant, which could reveal considerable quantities of steam being wasted by venting to the atmosphere or through defective steam traps, uninsulated lines, and passing through unused heat exchangers. Eliminating this end-use waste could produce greater savings than those easily and quickly developed by improving boiler efficiency. This approach requires care to ensure cost-effective use of time. It may not be cost-effective to track down every end use.

When conducting an energy audit, it is important to become familiar with operating and maintenance procedures and personnel. The energy manager can then recommend, through appropriate departmental channels, energy-saving operating and maintenance procedures. The energy manager should determine, through continued personal observation, the effectiveness of the recommendations.

Stewart et al. (1984) tabulated 139 different energy audit input procedures and forms for 10 different building types, each using 62 factors. They discuss features of selected audit forms that can help develop an audit procedure. A detailed process for conducting audits is outlined in *Procedures for Commercial Building Energy Audits* (ASHRAE 2004).

IMPROVING DISCRETIONARY OPERATIONS

Basic Energy Management

Control Energy System Use. The most effective method to reduce energy costs, both economically and environmentally, is through discretionary operations, such as turning off energy systems when they provide no benefit. Management of existing

Table 6 1997 Residential Energy Consumption

	Total Households, 10^6	Per Household, 10^6 Btu		Total Households, 10^6	Per Household, 10^6 Btu
Total Households	101.5	101.0	Climate zone (*continued*)		
Weekday Home Activities			5500 to 7000 HDD	28.0	127.8
Home used for business			4000 to 5499 HDD	22.5	105.5
Yes	7.4	114.4	Under 4000 HDD	19.5	74.3
No	94.1	99.9	>2000 CDD, <4000 HDD	22.2	76.6
Energy-intensive activity			**Type of Housing Unit**		
Yes	2.4	121.4	Single-family	73.7	114.7
No	99.1	100.5	Multifamily		
Someone home all day			2 to 4 units	5.6	91.5
Yes	51.3	106.7	5 or more units	15.8	48.6
No	50.1	95.1	Mobile home	6.3	79.5
Winter Temperature Settings			Heated Floorspace (square feet)		
Lower when no one home			Fewer than 600	7.9	61.1
Yes	45.5	99.9	600 to 999	21.5	77.4
No	56.0	101.8	1000 to 1599	30.4	97.4
Lower during sleeping hours			1600 to 1999	15.3	116.6
Yes	47.4	101.6	2000 to 2399	7.9	124.3
No	54.0	100.4	2400 to 2999	5.3	137.7
Use a secondary heating fuel			3000 or more	4.1	175.2
Yes	34.3	116.0	No estimate provided	9.1	101.5
No	66.5	94.0	Year of Construction		
Adequacy of insulation			1949 or before	27.9	124.8
Well Insulated	38.0	98.6	1950 to 1959	12.5	106.1
Adequately Insulated	44.4	102.5	1960 to 1969	14.4	96.0
Poorly Insulated	18.5	103.0	1970 to 1979	19.6	87.4
Central air conditioning use			1980 to 1989	17.3	81.7
All summer	24.6	97.9	1990 to 1997	9.7	94.6
Quite a bit	10.4	103.1	**All Utilities Paid By Household**		
Only a few times	12.4	103.5	All major fuels		
No central system	53.7	101.6	Yes	89.7	104.3
Room air conditioning use			No	11.8	75.3
All summer	5.7	96.3	Electricity		
Quite a bit	6.6	113.3	Yes	96.2	103.0
Only a few times	13.5	107.5	No	5.3	65.0
No room units	75.0	99.0	Natural gas		
Use a dishwasher			Yes	53.3	123.5
Yes	50.9	109.6	No	8.6	78.8
No	50.6	92.2	Fuel oil		
Use a clothes washer			Yes	7.6	145.8
Yes	78.5	112.3	No	2.3	91.9
No	22.9	62.2	LPG		
Use a clothes dryer			Yes	7.9	103.8
Yes	72.2	113.7	No	0.2	88.5
No	29.3	69.5	Kerosene		
Use two or more refrigerators			Yes	3.5	100.5
Yes	15.4	135.0	No		
No	86.1	94.9	1997 Family Income		
Outdoor lights on all night			Less than $10,000	13.3	76.4
Yes	26.3	108.2	$10,000 to $24,999	29.1	87.3
No	75.2	98.4	$25,000 to $49,999	31.1	102.6
Census Region and Division			$50,000 or more	27.9	125.2
Northeast	19.7	120.6	Below Poverty Line		
New England	5.3	122.9	100%	14.6	83.0
Middle Atlantic	14.4	119.7	125%	19.7	82.9
Midwest	24.1	134.0	150%	26.7	84.2
East North Central	16.9	138.2	Eligible for Federal assistance	34.1	86.7
West North Central	7.2	124.1	Age of Householder		
South	35.9	83.9	Under 25 years	5.7	69.7
South Atlantic	18.7	75.1	25 to 34 years	18.5	87.7
East South Central	6.3	87.7	35 to 44 years	23.2	107.4
West South Central	10.8	96.7	45 to 59 years	25.6	113.4
West	21.8	74.9	60 years and over	28.5	99.4
Mountain	6.2	94.0	Race of Householder		
Pacific	15.6	67.3	White	78.5	103.9
Largest populated states			Black	12.7	105.3
California	11.5	63.9	Other	10.3	72.8
Florida	5.9	54.9	Householder of Hispanic descent		
New York	6.8	123.4	Yes	9.4	75.9
Texas	7.0	96.1	No	92.1	103.5
Urban/rural location			Household Size		
City	48.2	95.8	1 person	25.6	74.7
Town	18.2	104.2	2 persons	33.0	101.2
Suburbs	18.6	110.4	3 persons	17.4	109.5
Rural	16.5	101.9	4 persons	15.2	117.7
Climate zone			5 persons	6.4	123.9
<2000 CDD, >7000 HDD	9.3	123.1	6 or more persons	3.9	129.6

Source: www.eia.doe.gov/emeu/recs/recs97 Tables CE1. CDD = cooling degree-day (65°F base); HDD = heating degree-day (65°F base).

systems and design of new ones should emphasize ease and simplicity of system control. For example, an energy management system may be effective in large and complicated buildings, but inappropriate for smaller buildings or in those with rapid turnover of operators who are unfamiliar with the building systems.

Extensive labeling and inclusive, clear instruction on how to operate these systems lead to better control of their use. Ways to conserve energy include the following:

- Shut down HVAC&R systems when not required
- Reduce air leakage
- Reduce ventilation rates during periods of low occupancy
- Shut down exhaust fans when not required
- Seal or repair leaks in ducts and pipes
- Reduce water leakage
- Turn off lighting: remove unnecessary lighting, add switched circuits, use motion sensors and light-sensitive controls
- Use temperature setup and setback
- Cool with outside air
- Seal unused vents and ducts to the outside
- Tune up systems before heating and cooling seasons
- Take transformers offline during idle periods
- Disconnect or turn off all nonessential loads
- Educate tenants and occupants

Purchase Lower-Cost Energy. This is the second most effective method for reducing energy costs for all owners and operators. Building operators and managers must understand all the options in purchasing energy and design systems to take advantage of changing energy costs. The following options should be considered:

- Choosing or negotiating lower-cost utility rates
- Procuring electricity or fuels through brokers
- Correcting power factor penalties
- Controlling peak electric billing demand
- Utility-sponsored demand response programs
- Transportation and interruptible natural gas rates
- Cogeneration
- Lower-cost liquid fuels
- Increasing volume for onsite storage
- Avoiding sales or excise taxes where possible
- Incentive rebates from utilities and manufacturers

Optimize Energy Systems Operation. The third most effective method for reducing energy costs is to tune energy systems to optimal performance, an ongoing process combining training, preventive maintenance, and system adjustment. Tasks for optimizing performance include the following:

- Training operating personnel
- Tuning combustion equipment
- Adjusting gas burners to optimal efficiency
- Following an established maintenance program
- Cleaning or replacing filters
- Cleaning fan blades and ductwork
- Cycling ventilation systems to coincide with occupied spaces
- Using water treatment

Purchase Efficient Replacement Systems. This method is more expensive than the other three, presents energy managers with the greatest liability, and may be less cost-effective. Because the greatest profit by suppliers is made by system replacement, it often draws the greatest attention from building owner/operators and equipment suppliers. It is critical to ensure that possible equipment or system replacements are objectively evaluated to confirm both the replacement costs and benefits to the owner. The optimum time for replacing less-efficient equipment is near the end of its expected life or when major repairs are needed. Systems that may be replaced include the following:

- Lighting systems and lamps
- Heating and cooling equipment
- Energy distribution systems (pumps and fans)
- Motors
- Thermal envelope components
- Industrial process equipment
- Controls and energy management systems

Optimizing More Complex System Operation

Basic energy management is appropriate for many types of facilities, but as the level of complexity of building systems increases, additional strategies are needed to optimize energy systems. Approaches include **recommissioning**, **retrocommissioning**, and **ongoing commissioning**. See Chapter 42 for more information on these approaches.

This approach to reducing energy costs typically requires a strong team effort on the part of the facility staff and a consultant team to identify and fix comfort problems in the building, accompanied by an aggressive approach to optimizing HVAC operation and control in the building. It is most effective when preceded by installation of good energy metering and a strong energy accounting program. Some important measures typically implemented include the following:

- Optimizing hot and cold deck reset schedules
- Optimizing duct static pressure reset schedules
- Optimizing pump control
- Optimizing terminal box settings/control
- Optimizing sequencing and water temperature reset schedules of boilers and chillers
- Diagnosing and fixing fundamental causes of comfort problems
- Diagnosing and repairing stuck or leaky valves and dampers
- Training operating personnel in optimum operating strategies
- Using diagnostic tools, data loggers, etc., to diagnose equipment function

Implementing these measures has been found to reduce energy use by an average of about 20% (Claridge et al. 1998). Approaches to commissioning and optimizing operation of existing buildings can be found in Claridge and Liu (2000), Haasl and Sharp (1999), and Liu et al. (1997).

ENERGY CONSERVATION OPPORTUNITIES

Identifying Energy Conservation Opportunities

Various energy conservation opportunities (ECOs) can be quantitatively evaluated from end-use energy profiles. Important considerations in this process are as follows:

- System interaction
- Utility rate structure
- Payback
- Alignment with corporate goals
- Installation requirements
- Life of the measure
- Energy measurement and verification requirements
- Maintenance costs
- Tenant/occupant comfort
- Effect on building operation and appearance

Accurate energy savings calculations can be made only if system interaction is allowed for and fully understood. Annual simulation models may be necessary to accurately estimate the interactions between various ECOs.

Using average costs per unit of energy in calculating the energy cost avoidance of a particular measure is likely to result in incorrect energy costs and cost avoidance, because actual energy cost avoidance may not be proportional to the energy saved, depending on the billing method for energy used.

PNNL (1990) discusses 118 ECOs, including the following:

Boilers	Outside air ventilation control
Condensate systems	Envelope infiltration
Water treatment	Weatherstripping
Fuel acquisition	Caulking
Fuel systems	Vestibules
Chillers	Steam distribution
Vapor barrier	Hydronic systems
Glazing	Pumps
Piping insulation	Steam traps
Instrumentation	Domestic water heating
Shading	Trombe walls
Fixtures	Thermal shutters
Swimming pools	Surface color
Cooling towers	Roof covering
Condensing units	Lamps
Air-handling units	Ballasts
Unitary equipment	Light switching options
Outside air control	Photo cell controls
Balancing	Demand limiting
Shutdown	Current leakage
Power factor correction	Minimizing reheat
Energy recovery	Power distribution
Filters	Cooking practices
Humidification	Refrigeration
Dishwashing	System air leakage
Vending machines	System interaction
Heat/cool storage	Space segregation
Time-of-day rates	Computer controls
Cogeneration	Heat pumps
Active solar systems	Staff training
Occupant indoctrination	Documentation
Controls	Thermostats
Setback	Space planning
T5 lighting	Variable-frequency drives (VFDs)

In addition, previously implemented energy conservation measures should be evaluated to (1) ensure that devices are in good working order and measures are still effective, and (2) consider revising them to reflect changes in technology, building use, and/or energy cost.

Evaluating Energy Conservation Opportunities

Once a list of ECOs is established, it should be evaluated and implemented. In establishing ECO priorities, the capital cost, cost-effectiveness, effect on indoor environment, and resources available must be considered. Factors involved in evaluating the desirability of a particular energy conservation retrofit measure are as follows:

- Rate of return (simple payback, life-cycle cost, net present value)
- Total savings (energy, cost avoidance)
- Initial cost (required investment)
- Other benefits (safety, comfort, improved system reliability, improved productivity)
- Liabilities (increased maintenance costs, potential obsolescence)
- Risk of failure (confidence in predicted savings, rate of increase in energy costs, maintenance complications, success of others with the same measures)

Some owners are reluctant to implement ECOs because of bad experiences with energy projects. To reduce the risk of failure, documented performance of ECOs in similar situations should be obtained and evaluated. One common problem is that energy consumption for individual end uses is overestimated, and the predicted savings are not achieved. When doubt exists about energy consumption, temporary measurements should be made and evaluated. Causes of past failures should be analyzed carefully to minimize the possibility of their reoccurrence.

Resources available for an energy conservation retrofit opportunity should include the following:

- Management attention, commitment, and follow-through
- Skills
- Manpower
- Investment capital

Heating Effects of Electrical Equipment

Electrical equipment and appliances, from lighting systems and office equipment to motors and water heaters, provide the useful services they are designed to produce. However, the electrical energy they use also appears as heat within the building, which can either be useful or detrimental to the building's HVAC systems, depending on the season. In cold weather, heat produced by electrical equipment can help reduce the load on the building's heating system. In contrast, during warm weather, heat produced by electrical appliances adds to the building's air-conditioning load.

Energy-efficient equipment and appliances consume less energy to produce the same useful work, but they also produce less heat. As a result, efficient electrical equipment increases the load on heating systems in winter and reduces the load on air-conditioning systems in summer. Effects of energy-efficient equipment and appliances on energy use for building heating and air conditioning systems are commonly called **interactive effects** or **cross effects**.

When considering the overall net savings of an energy conservation opportunity, it is important to consider its interactive effects on building heating, cooling, and refrigeration systems. Weighing the interactive effects results in better-informed decisions and realistic expectations of savings.

The percentage of heat that is useful in your specific building or room depends on several factors, including the following:

- Location of light fixtures
- Location of heaters and their thermostats
- Type of ceiling
- Size of building
- Whether room is an interior or exterior space
- Extent of heating and cooling seasons
- Type of heating, ventilation, and air-conditioning system used in each room

Unfortunately, interactive effects are often quite complex and may require assessment by a specialist; for details, see Rundquist et al. (1993).

Exploring Financing Options

Financing alternatives also need to be considered. When evaluating proposed energy management projects, particularly those with a significant capital cost, it is important to include a life-cycle cost analysis. This not only provides good information about the financial attractiveness (or otherwise) of a project, but also assures management that the project has been carefully considered and evaluated before presentation.

Several life-cycle cost procedures are available. Chapter 36 contains details on these and other factors that should be considered in such an analysis.

Capital for energy-efficiency improvements is available from various public and private sources, and can be accessed through a wide and flexible range of financing instruments. There are variations and combinations, but the five general mechanisms for financing investments in energy efficiency are the following:

- **Internal funds**, or direct allocations from an organization's own internal capital or operating budget
- **Debt financing**, with capital borrowed directly by an organization from private lenders

- **Lease** or **lease-purchase agreements**, in which equipment is acquired through an operating or financing lease with little or no upfront costs, and payments are made over five to ten years
- **Energy performance contracts**, in which improvements are financed, installed, and maintained by a third party, which guarantees savings and payments based on those savings
- **Utility (or other) incentives**, such as rebates, grants, or other financial assistance offered by an energy utility (or other provider of efficiency public benefits funding) for design and purchase of energy-efficient systems and equipment

An organization may use several of these financing mechanisms in various combinations. The most appropriate set of options depends on the type of organization (public or private), size and complexity of a project, internal capital constraints, in-house expertise, and other factors (Turner 2001).

IMPLEMENTING ENERGY CONSERVATION MEASURES

When all desirable ECOs have been considered and a list of recommendations is developed, a report should be prepared for management. Each recommendation should include the following:

- Present condition of the system or equipment to be modified
- Recommended action
- Who should accomplish the action
- Necessary documentation or follow-up required
- Measurement and verification protocol to be used
- Potential interferences to successful completion
- Disruption to workplace or production
- Staff effort and training required
- Risk of failure
- Interactions with other end uses and ECOs
- Economic analysis (including payback, investment cost, and estimated savings figures) using corporate economic evaluation criteria
- Schedule for implementation

The energy manager must be prepared to sell the plans to upper management. Energy conservation measures (ECMs) must generally be financially justified if they are to be adopted. Every organization has limited funds available that must be used in the most effective way. The energy manager competes with others in the organization for the same funds. A successful plan must be presented in a form that is easily understood by the decision makers. Finally, the energy manager must present nonfinancial benefits, such as improved product quality or the possibility of postponing other expenditures.

After approval by management, the energy manager directs the completion of energy conservation retrofit measures. If utility rebates are used, the necessary approvals should be acquired before proceeding with the work. Some measures require that an architect or engineer prepare plans and specifications for the retrofit. The package of services required usually includes drawings, specifications, assistance in obtaining competitive bids, evaluation of the bids, selection of the contractors, construction observation, final check-out, and assistance in training personnel in the proper application of the revisions.

MONITORING RESULTS

Once energy conservation measures are under way, procedures need to be established to record, frequently and regularly, energy consumption and costs for each building and/or end-use category in a manner consistent with functional cost accountability. Turner et al. (2001) found that consumption increased by more than 5% over two years because of component failures and controls changes after implementing optimum practices in a group of 10 buildings. Data may be obtained from the utility, but additional metering may be

needed to monitor energy consumption accurately. Metering can use devices that automatically read and transmit data to a central location, or less expensive metering devices that require regular readings by building maintenance and/or security personnel. Costs for automatic metering devices, such as adding points to a DDC system, must be weighed against the benefits. Many energy managers find it helpful to collect energy consumption information hourly. However, if the energy manager is not able to evaluate data as frequently as it is collected, it may be more practical to collect data less frequently.

The energy manager should review data while they are current and take immediate action if profiles indicate a trend in the wrong direction. These trends could be caused by uncalibrated controls, changes in operating practices, or mechanical system failure, all of which are problems that should be isolated and corrected as soon as possible.

EVALUATING SUCCESS AND ESTABLISHING NEW GOALS

Comparing facility performance before and after implementing ECOs is useful. It helps keep operating staff on track with their energy conservation efforts, ensuring that utility consumptions do not return to preproject levels (assuming occupancy and facility size remain unchanged). It also convinces other staff and tenants that the process is worthwhile. When utility costs increase, energy conservation measures are seen as that much more prudent and rewarding.

Once initial goals have been established, tracking their performance becomes the key to success. Original ECMs would be reviewed and shared with building occupants and operators before implementation. The combination of feedback from both these parties on building comfort and operation with the ongoing analysis of analyzing energy bills provides the building or energy manager with the necessary information to identify a successful measure.

After evaluating the ECMs, new goals may be established or existing ones revised. This step allows energy management staff to prove that they are accountable to building owners and occupants alike. Reviewing goals frequently maintains energy conservation effectiveness and the associated cost savings by separating good initiatives from the less good. Setting new energy management goals can discourage complacency among building operators and occupants so that the overall effort does not diminish.

Evaluating and reporting energy performance involves four steps:

1. Establishing key performance indicators
2. Tracking performance
3. Developing new goals
4. Reporting

Establish Key Performance Indicators

When developing the energy management program, it is important to determine its performance factors of the energy management program. These factors are expressed in terms of key performance indicators (KPIs).

Suggested key performance indicators of a facilities performance as compared to other facilities of similar type are:

- Energy use index (EUI), total energy use per unit of gross floor area
- Cost utilization index (CUI), total energy cost per unit of total gross floor area
- Electrical energy use per unit of total gross floor area

The definition of key performance indicators provides the foundation for determining what data need to be collected, how often to collect it, and how to present it to senior management, the building owner, or relevant agency. Using the KPI method, only the total amount of data required to accomplish primary goals is reported to

senior management. All additional energy information is used to help understand whether facility performance is on track with goals.

Energy Policy Act. The Energy Policy Act (EPAct 2005) set goals for federal buildings to decrease their energy consumption by 2% per year between 2006 and 2015, compared to a baseline of 2004 consumption. (Thus, by 2010, for instance, the target percentage reduction from 2004 values is 10%.) Using this initiative, the following sample KPI definition could be used:

- 2000 benchmark measurement = energy use per unit area, reduced by 4% to set 2007 target, and by 10% to set the 2010 target, and by 16% to set the 2013 target
- Energy use data, summed monthly and annually for reporting against targets

At the end of each year, actual consumption is determined to generate an energy performance report for management.

ENERGY STAR® Tools. The U.S. Environmental Protection Agency's ENERGY STAR Web site offers the free online benchmarking tool, Target Finder (I-P units only; accessible from www.energystar.gov/index.cfm?c=new_bldg_design.bus_target_finder). This tool compares actual building performance to target values, and to other similar buildings. Figure 4 shows sample results for the Atlanta example building's general office space (omitting the computer center's floor space and electricity use). ENERGY STAR also offers an online Portfolio Manager (www.energystar.gov/index.cfm?c=evaluate_performance.bus_portfoliomanager), which provides secure performance data management and benchmarking for multiple buildings. Annual benchmarking with these (or similar) tools helps track improvements, both over time and in comparison with other buildings.

Tracking Performance

The next step is to build data displays using the data and models. The displays should be able to provide high-level KPI views to give an overall indication of energy performance, and to drill down to identify why a plan may not be on track.

DDC systems can monitor energy performance and notify the energy engineer when energy usage is off track. Daily monitoring can be a valuable, proactive tool.

For example, using the data presented in Table 1, a daily target usage/day could be determined based on outside air temperature and

building occupancy schedule. If the daily use rises above the target use by a predetermined amount, the DDC system can indicate an alarm and send a notification to the energy manager's pager or cell phone. The energy manager then can investigate the cause of the discrepancy. When implementing this type of performance monitoring strategy, it is important that the measurement and verification plan provide standard operating procedures (SOPs) to facilitate troubleshooting of energy performance alarms. Procedures are discussed in ANSI/ASHRAE *Standard* 105.

Developing New Goals

Implementing the baseline model is a three-step process: (1) the baseline period is selected, (2) the baseline model is created, and (3) one or more target models are identified to track energy performance. The baseline period should most closely reflect the current or expected building use and occupancy.

Using utility bill data to create a steady-state baseline model of energy consumption for each building. Steady-state models are useful when using monthly, weekly, or daily data. For more information on steady-state, data-driven models, see Chapter 32 of the 2005 *ASHRAE Handbook—Fundamentals*.

Utility bills for an entire year are collected and used for baseline development. Many energy managers use spreadsheets to compile and compare the data.

Cooling degree-days and heating degree-days are commonly used to track successes compared to ECM targets with respect to weather-dependent energy consumption. Local CDD and HDD information is traditionally based on a balance point of 65°F. The balance point for a building is that outdoor ambient temperature at which the building requires neither mechanical heating or cooling to maintain the indoor occupied temperature set point; 65°F is not typically the actual balance point for any commercial or residential building. Therefore, regional or local HDD from weather stations or utilities are only a general reference point. A building's weather-affected energy consumption may be calculated by using spreadsheets, regression analysis, or building energy modeling software. The tools used to determine a building's balance point depends on the energy manager's analytical aptitude. Further information on energy estimating using degree-days and balance points can be found in Chapter 32 of the 2005 *ASHRAE Handbook—Fundamentals*.

For larger, more complex facilities and where an building manager has a higher level of analytical experience, regression analysis could be used to analyze energy consumption. Through linear regression, utility bills are normalized to their daily average values. Repeated regression is done until the regression data represents the best fit to the utility bill data. Figure 5 shows the scatter plot of a

Fig. 4 ENERGY STAR® Rating for Atlanta Building
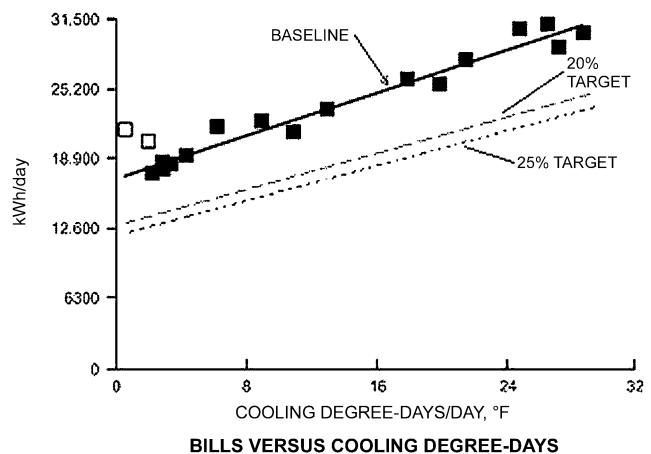
Fig. 5 Scatter Plot, Showing Best-Fit Baseline Model and Target Models
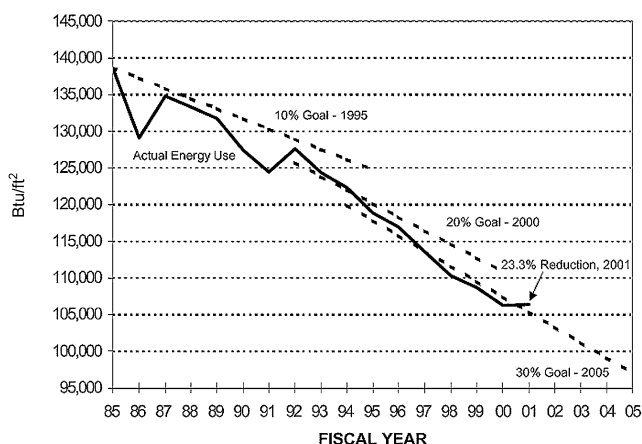
Fig. 6 Progress Toward Energy Reduction Goals for Federal Standard Buildings
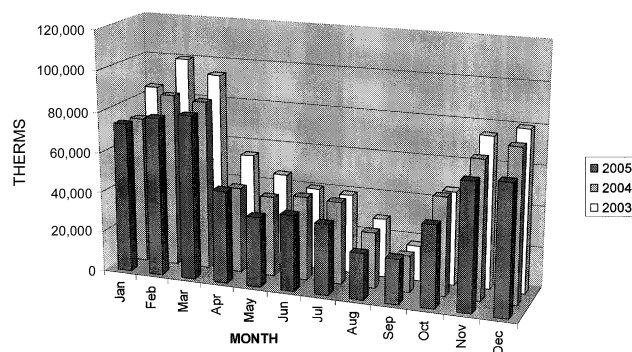
Fig. 7 Monthly Comparison of Natural Gas Use by Year

best-fit baseline and target models. In this example, cooling degree-days significantly affected building energy consumption, with a best fit for a base temperature (balance point) of 54°F (Sonderegger 1998). Reducing the slope and intercept constants of the baseline by 20% creates a straight-line model equation that represents a target goal for a 20% energy reduction.

The utility bill data steady-state model is also referred to as whole-building measurement and verification. More information about this process can be found in ASHRAE *Guideline* 14 and EVO (2002).

Reporting

Energy performance based on ECMs must be reported to senior management, building operators, and tenants. Reporting can be monthly, quarterly, or annual. When developing presentation materials to document energy performance, make sure that report content shows performance as related to key performance indicators (KPIs) used by the organization.

Figure 6 shows progress toward energy reduction goals for federal buildings presented to the U.S. Congress for fiscal year 2001 (DOE 2004). The figure compares energy performance against energy goals established in 1999.

Reports must be easy to understand by their readers. Keep management aware of the progress of changes to resource consumption, utility costs, and any effects, positive or negative, on the indoor environment, as perceived by staff. Provide information on any major activities, savings to date, and future planned activities. Provide narrative reports with pie charts or bar graphs of cost per resource. Figure 7 shows an example of monthly gas use in a facility from year to year.

Reports should contain information that is pertinent to the audience. Whereas a report to the company's administration would show how efforts of the energy management program affect operating and maintenance costs, a separate report to the operations staff might show how their daily decisions and actions change daily load profiles.

Bar graphs can compare a breakdown of annual costs for each resource to the base year or previous years, to show trends. Monthly comparisons (e.g., July over July) identify seasonal efforts. These annual costs may also be shown as compared to data for similar facilities, which may be available from local utilities.

BUILDING EMERGENCY ENERGY USE REDUCTION

The need for occasional reductions in energy use during specific periods has increased because of rising energy costs and supply reductions (voluntary or mandatory) or equipment failures. Emergencies include short-term shortages of a particular energy source brought about by natural disasters, extreme weather conditions, utility system equipment disruptions, labor strikes, failures in building systems or equipment, self-imposed cutbacks in energy use, world political activities, or other forces beyond the control of the building owner and operator. Recently, some areas have been subject to electric power supply constraints, with building owners and managers asked or required to cut their electricity consumption for short- or long-term periods. In limited instances, utilities have implemented rolling blackouts, requested voluntary reductions, and asked users to operate emergency generators.

A more challenging case occurred in August 2003 in the northeastern United States and eastern Canada, when a major blackout required numerous cities to implement contingency plans. The International Facilities Management Association (IFMA) surveyed its members to learn what their contingency plans had been, why they were created, and how well they worked (IFMA 2003). Research such as this can help building operators and managers develop emergency energy use reduction plans.

This section provides information to help building owners and operators maintain the best operating condition for the facilities during various energy emergencies, whether electric or fossil fuel in nature.

Implementing Emergency Energy Use Reductions

Each building owner, lessor, and operator should use the energy team approach and identify an individual with the necessary authority and knowledge to review and fit recommendations into a plan for the particular building or complex of buildings. Because energy reduction requirements may occur with little or no advance notice, plans should be developed and reviewed by the energy team in advance. Each type of energy emergency requires a specific plan to reduce building energy use and still maintain the best building environment under the circumstances. The plan should include measures to reduce specific types of energy use in the building, as well as provisions for both slight and major energy use reduction. Implementation of particular recommendations should then be coordinated through building occupants and operators, with assistance from the responsible party as necessary. In some cases, existing building energy management systems can be used to implement demand shedding. The plan should be tested occasionally.

Depending on the type of building, its use, the energy source(s) for each function, and local conditions such as climate and availability of other similar buildings, the following steps should be taken in developing a building emergency energy use reduction plan:

1. Develop a list of measures applicable to the building.
2. Estimate the amount and type of energy savings for each measure and appropriate combination of measures (e.g., account for air-conditioning savings from reduced lighting and other internal

loads). Tabulate demand and usage savings separately for response to different types of emergencies.

3. For various levels of possible energy emergency, develop a plan that maintains the best building environment under the circumstances. Develop the plan so that actions taken can be energy-source-specific. That is, group actions to be taken to reduce energy consumption for each type of energy used in the building. Include both short- and long-term measures in the plan. Operational changes may be implemented quickly and prove adequate for short-term emergencies.

4. Experiment with the plan developed, record energy consumption and demand reduction data, and revise the plan as necessary. Much of the experimentation may be done on weekends to minimize disruption.

5. Meet with the local utility provider(s) and back-up fuel suppliers to review the plan.

6. Meet with building occupants annually to review the plan to ensure that actions taken do not cause major disruptions or compromise life safety or security provisions. Establish a procedure for notification of building occupants before actions are taken. Cellular phones may not be a reliable means of communication in some circumstances.

7. Be certain that there is a plan to minimize entrapment of occupants in elevators in case of a rolling blackout or other emergency disruptions.

8. Review the plan annually with building security and the fire department to ensure that emergency efforts are not hindered by the plan and to ensure that security or emergency people know what to expect (reduced lighting, lower temperatures, elevators out of operation, etc.).

9. When preparing the plan, **do not**
   • Take lighting fixtures out of service that are on night lighting circuits, provide lighting for security cameras, or provide egress lighting during a power failure
   • Remove elevators or lifts from service that will be required for emergency or ADA purposes
   • Reduce ventilation or exhaust in laboratories or other areas where hazardous conditions exist

Some measures can be implemented permanently. Depending on the level of energy emergency and the building priority, the following actions may be considered in developing the plan for emergency energy reduction in the building, keeping in mind the applicability for each individual building or system:

General
• Change operating hours
• Move personnel into other building areas (consolidation)
• Ensure that emergency generators are tuned up and run frequently enough to increase dependability, service the expected electrical load, and keep alternative fuel supply at optimal level
• Shut off nonessential equipment
• Review the amount of uninterruptible power supply (UPS) time available for critical equipment, and upgrade if necessary

Thermal Envelope
• Use all existing blinds, draperies, and window coverings
• Install interior window insulation
• Caulk and seal around unused exterior doors and windows (but do not seal doors required for emergency egress or that may be required by the fire department in an emergency).
• Install solar shading devices in summer
• Seal all unused vents and ducts to outside

HVAC Systems and Equipment
• Modify controls or control set points to raise and lower temperature and humidity as necessary
• Shut off or isolate all nonessential equipment and spaces
• Tune up equipment

• Lower thermostat set points in winter
• Raise chilled-water temperature
• Lower hot-water temperature (*Note*: Keep hot-water temperature higher than 145°F if a noncondensing gas boiler is used)
• Reduce or eliminate reheat
• Reduce (and eliminate during unoccupied hours) mechanical ventilation and exhaust airflow
• Raise thermostat set points in summer or turn cooling equipment off
• Reduce amount of recooling in summer
• Reduce duty cycling on HVAC systems (on later, off earlier)

Lighting Systems
• Evaluate overlit areas and remove lamps or reduce lamp wattage
• Use task lighting where appropriate
• Move building functions to exterior or daylit areas
• Turn off electric lights in areas with adequate natural light
• Clean all lamps and luminaires
• Revise building cleaning and security procedures to minimize lighting periods
• Consolidate parking and turn off unused parking security lighting

Special Equipment
• Take transformers offline during periods of nonuse
• Shut off or regulate the use of vertical transportation systems
• Shut off unused or unnecessary equipment, such as photocopiers, music systems, and computers
• Reduce or turn off potable hot-water supply

Building Operation Demand Reduction
• Sequence or interlock heating or air-conditioning systems
• Disconnect or turn off all nonessential loads
• Reduce lighting levels
• Preheat or precool, if possible, before utility-imposed emergency periods

When Power Is Restored
• To prevent overloading the system, turn equipment back on gradually
• Test and verify proper operation of critical equipment, security, and fire and smoke alarms
• Check monitors on temperature-sensitive equipment
• Discuss lessons learned with staff and make any necessary changes to emergency plan
• Restock whatever emergency supplies were used, including alternative fuels

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CHAPTER 36

OWNING AND OPERATING COSTS

OWNING and operating cost information for the HVAC system should be part of the investment plan of a facility. This information can be used for preparing annual budgets, managing assets, and selecting design options. Table 1 shows a representative form that summarizes these costs.

A properly engineered system must also be economical, but this is difficult to assess because of the complexities surrounding effective money management and the inherent difficulty of predicting future operating and maintenance expenses. Complex tax structures and the time value of money can affect the final engineering decision. This does not imply use of either the cheapest or the most expensive system; instead, it demands intelligent analysis of financial objectives and the owner's requirements.

Certain tangible and intangible costs or benefits must also be considered when assessing owning and operating costs. Local codes may require highly skilled or certified operators for specific types of equipment. This could be a significant cost over the life of the system. Similarly, such intangible items as aesthetics, acoustics, comfort, safety, security, flexibility, and environmental impact may vary by location and be important to a particular building or facility.

OWNING COSTS

The following elements must be established to calculate annual owning costs: (1) initial cost, (2) analysis or study period, (3) interest or discount rate, and (4) other periodic costs such as insurance, property taxes, refurbishment, or disposal fees. Once established, these elements are coupled with operating costs to develop an economic analysis, which may be a simple payback evaluation or an in-depth analysis such as outlined in the section on Economic Analysis Techniques.

Initial Cost

Major decisions affecting annual owning and operating costs for the life of the building must generally be made before completion of contract drawings and specifications. To achieve the best performance and economics, comparisons between alternative methods of solving the engineering problems peculiar to each project should be made in the early stages of design. Oversimplified estimates can lead to substantial errors in evaluating the system.

The evaluation should lead to a thorough understanding of installation costs and accessory requirements for the system(s) under consideration. Detailed lists of materials, controls, space and structural requirements, services, installation labor, and so forth can be prepared to increase accuracy in preliminary cost estimates. A reasonable estimate of capital cost of components may be derived from cost records of recent installations of comparable design or from quotations submitted by manufacturers and contractors, or by

The preparation of this chapter is assigned to TC 7.8, Owning and Operating Costs.

Table 1 Owning and Operating Cost Data and Summary

OWNING COSTS

I. Initial Cost of System	_____
II. Periodic Costs	
A. Income taxes	_____
B. Property taxes	_____
C. Insurance	_____
D. Rent	_____
E. Other periodic costs	_____
Total Periodic Costs	_____
III. Replacement Cost	_____
IV. Salvage Value	_____
Total Owning Costs	_____

OPERATING COSTS

V. Annual Utility, Fuel, Water, etc., Costs	
A. Utilities	
1. Electricity	_____
2. Natural gas	_____
3. Water/sewer	_____
4. Purchased steam	_____
5. Purchased hot/chilled water	_____
B. Fuels	
1. Propane	_____
2. Fuel oil	_____
3. Diesel	_____
4. Coal	_____
C. On-site generation of electricity	_____
D. Other utility, fuel, water, etc., costs	_____
Total	_____
VI. Annual Maintenance Allowances/Costs	
A. In-house labor	_____
B. Contracted maintenance service	_____
C. In-house materials	_____
D. Other maintenance allowances/costs	_____
(e.g., water treatment)	
Total	_____
VII. Annual Administration Costs	_____
Total Annual Operating Costs	_____

TOTAL ANNUAL OWNING AND OPERATING COSTS   _____

36.1

Table 2   Initial Cost Checklist

Energy and Fuel Service Costs

Fuel service, storage, handling, piping, and distribution costs
Electrical service entrance and distribution equipment costs
Total energy plant

Heat-Producing Equipment

Boilers and furnaces
Steam-water converters
Heat pumps or resistance heaters
Makeup air heaters
Heat-producing equipment auxiliaries

Refrigeration Equipment

Compressors, chillers, or absorption units
Cooling towers, condensers, well water supplies
Refrigeration equipment auxiliaries

Heat Distribution Equipment

Pumps, reducing valves, piping, piping insulation, etc.
Terminal units or devices

Cooling Distribution Equipment

Pumps, piping, piping insulation, condensate drains, etc.
Terminal units, mixing boxes, diffusers, grilles, etc.

Air Treatment and Distribution Equipment

Air heaters, humidifiers, dehumidifiers, filters, etc.
Fans, ducts, duct insulation, dampers, etc.
Exhaust and return systems
Heat recovery systems

System and Controls Automation

Terminal or zone controls
System program control
Alarms and indicator system
Energy management system

Building Construction and Alteration

Mechanical and electric space
Chimneys and flues
Building insulation
Solar radiation controls
Acoustical and vibration treatment
Distribution shafts, machinery foundations, furring

consulting commercially available cost-estimating guides and software. Table 2 shows a representative checklist for initial costs.

Analysis Period

The time frame over which an economic analysis is performed greatly affects the results. The analysis period is usually determined by specific objectives, such as length of planned ownership or loan repayment period. However, as the length of time in the analysis period increases, there is a diminishing effect on net present-value calculations. The chosen analysis period is often unrelated to the equipment depreciation period or service life, although these factors may be important in the analysis.

Service Life

For many years, this chapter has included estimates of service lives for various HVAC system components, based on a survey conducted in 1976 under ASHRAE Research Project RP-186 (Akalin 1978). These estimates have been useful to a generation of practitioners, but changes in technology, materials, manufacturing techniques, and maintenance practices now call into question the continued validity of the original estimates. For this reason, ASHRAE funded research project TRP-1237 to develop an Internet-based data collection tool and database on HVAC equipment service life and maintenance costs, to allow equipment owning and operating

Table 3   Median Service Life

Equipment Type	Median Service Life, Years	Total No. of Units	No. of Units Replaced
DX air distribution equipment	>24	1907	284
Chillers, centrifugal	>25	234	34
Cooling towers, metal	>22	170	24
Boilers, hot-water, steel gas-fired	>22	117	24
Controls, pneumatic	>18	101	25
electronic	>7	68	6
Potable hot-water heaters, electric	>21	304	36

LIVE GRAPH
Click here to view
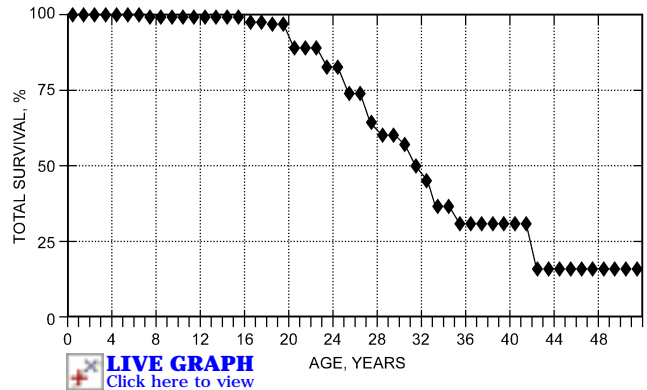
Fig. 1   Survival Curve for Centrifugal Chillers
[Based on data in Abramson et al. (2005)]

cost data to be continually updated and current. The database was seeded with information gathered from a sample of 163 commercial office buildings located in major metropolitan areas across the United States. Abramson et al. (2005) provide details on the distribution of building size, age, and other characteristics. Table 3 presents estimates of median service life for various HVAC components in this sample.

Median service life in Table 3 is based on analysis of survival curves, which take into account the units still in service and the units replaced at each age (Hiller 2000). Conditional and total survival rates are calculated for each age, and the percent survival over time is plotted. Units still in service are included up to the point where the age is equal to their current age at the time of the study. After that point, these units are censored (removed from the population). Median service life in this table indicates the highest age at which the survival rate remains at or above 50% while the sample size is 30 or more. There is no hard-and-fast rule about the number of units needed in a sample before it is considered statistically large enough to be representative, but usually the number should be larger than 25 to 30 (Lovvorn and Hiller 2002). This rule-of-thumb is used because each unit removal represents greater than a 3% change in survival rate as the sample size drops below 30, and that percentage increases rapidly as the sample size gets even smaller.

Figure 1 presents the survival curve for centrifugal chillers, based on data in Abramson et al. (2005). Note that, although the point at which survival rate drops to 50% based on all data in the survey is 31 years, the median service life based on a minimum sample size of 30 is approximately 25 years. For this reason, Table 3 gives the median service life of centrifugal chillers as >25 years.

Table 4 compares the estimates of median service life in Abramson et al. (2001) with those developed with those in Akalin (1978). Most differences are on the order of one to five years.

Estimated service life of new equipment or components of systems not listed in Table 3 may be obtained from manufacturers, associations, consortia, or governmental agencies. Because of the proprietary nature of information from some of these sources, the

Table 4 Comparison of Service Life Estimates

Equipment Item	Median Service Life, Years		Equipment Item	Median Service Life, Years		Equipment Item	Median Service Life, Years	
	Abramson et al. (2005)	Akalin (1978)		Abramson et al. (2005)	Akalin (1978)		Abramson et al. (2005)	Akalin (1978)
Air Conditioners			**Air Terminals**			**Condensers**		
Window unit	N/A*	10	Diffusers, grilles, and registers	N/A*	27	Air-cooled	N/A	20
Residential single or split package	N/A*	15	Induction and fan-coil units	N/A*	20	Evaporative	N/A*	20
Commercial through-the-wall	N/A*	15	VAV and double-duct boxes	N/A*	20	**Insulation**		
Water-cooled package	>24	15	**Air washers**	N/A*	17	Molded	N/A*	20
Heat pumps			**Ductwork**	N/A*	30	Blanket	N/A*	24
Residential air-to-air	N/A*	15[b]	**Dampers**	N/A*	20	**Pumps**		
Commercial air-to-air	N/A*	15	**Fans**	N/A*		Base-mounted	N/A*	20
Commercial water-to-air	>24	19	Centrifugal	N/A*	25	Pipe-mounted	N/A*	10
Roof-top air conditioners			Axial	N/A*	20	Sump and well	N/A*	10
Single-zone	N/A*	15	Propeller	N/A*	15	Condensate	N/A*	15
Multizone	N/A*	15	Ventilating roof-mounted	N/A*	20	**Reciprocating engines**	N/A*	20
Boilers, Hot-Water (Steam)			**Coils**			**Steam turbines**	N/A*	30
Steel water-tube	>22	24 (30)	DX, water, or steam	N/A*	20	**Electric motors**	N/A*	18
Steel fire-tube		25 (25)	Electric	N/A*	15	**Motor starters**	N/A*	17
Cast iron	N/A*	35 (30)	**Heat Exchangers**			**Electric transformers**	N/A*	30
Electric	N/A*	15	Shell-and-tube	N/A*	24	**Controls**		
Burners	N/A*	21	**Reciprocating compressors**	N/A*	20	Pneumatic	N/A*	20
Furnaces			**Packaged Chillers**			Electric	N/A*	16
Gas- or oil-fired	N/A*	18	Reciprocating	N/A*	20	Electronic	N/A*	15
Unit heaters			Centrifugal	>25	23	**Valve actuators**		
Gas or electric	N/A*	13	Absorption	N/A*	23	Hydraulic	N/A*	15
Hot-water or steam	N/A*	20	**Cooling Towers**			Pneumatic	N/A*	20
Radiant heaters			Galvanized metal	>22	20	Self-contained		10
Electric	N/A*	10	Wood	N/A*	20			
Hot-water or steam	N/A*	25	Ceramic	N/A*	34			

*N/A: Not enough data yet in Abramson et al. (2005). Note that data from Akalin (1978) for these categories may be outdated and not statistically relevant. Use these data with caution until enough updated data are accumulated in Abramson et al.

variety of criteria used in compiling the data, and the diverse objectives in disseminating them, extreme care is necessary in comparing service life from different sources. Designs, materials, and components of equipment listed in Table 3 have changed over time and may have altered the estimated service lives of those equipment categories. Therefore, establishing equivalent comparisons of service life is important.

As noted, service life is a function of the time when equipment is replaced. Replacement may be for any reason, including, but not limited to, failure, general obsolescence, reduced reliability, excessive maintenance cost, and changed system requirements (e.g., building characteristics, energy prices, environmental considerations). Service lives shown in the tables are based on the age of the equipment when it was replaced, regardless of the reason it was replaced.

Locations in potentially corrosive environments and unique maintenance variables affect service life. Examples include the following:

- **Coastal and marine environments**, especially in tropical locations, are characterized by abundant sodium chloride (salt) that is carried by sea spray, mist, or fog.

  Many owners require equipment specifications stating that HVAC equipment located along coastal waters will have corrosion-resistant materials or coatings. Design criteria for systems installed under these conditions should be carefully considered.
- **Industrial** applications provide many challenges to the HVAC designer. It is very important to know if emissions from the industrial plant contain products of combustion from coal, fuel oils, or releases of sulfur oxides (SO_2, SO_3) and nitrogen oxides (NO_x) into the atmosphere. These gases typically accumulate and return to the ground in the form of acid rain or dew.

Not only is it important to know the products being emitted from the industrial plant being designed, but also the adjacent upwind or downwind facilities. HVAC system design for a plant located downwind from a paper mill requires extraordinary corrosion protection or recognition of a reduced service life of the HVAC equipment.

- **Urban** areas generally have high levels of automotive emissions as well as abundant combustion by-products. Both of these contain elevated sulfur oxide and nitrogen oxide concentrations.
- **Maintenance** factors also affect life expectancy. The HVAC designer should temper the service life expectancy of equipment with a **maintenance factor**. To achieve the estimated service life values in Table 3, HVAC equipment must be maintained properly, including good filter-changing practices and good maintenance procedures. For example, chilled-water coils with more than four rows and close fin spacing are virtually impossible to clean even using extraordinary methods; they are often replaced with multiple coils in series, with a maximum of four rows and lighter fin spacing.

Depreciation

Depreciation periods are usually set by federal, state, or local tax laws, which change periodically. Applicable tax laws should be consulted for more information on depreciation.

Interest or Discount Rate

Most major economic analyses consider the opportunity cost of borrowing money, inflation, and the time value of money. **Opportunity cost** of money reflects the earnings that investing (or lending) the money can produce. **Inflation** (price escalation) decreases the purchasing or investing power (value) of future money because it can buy less in the future. **Time value** of money reflects the fact that

money received today is more useful than the same amount received a year from now, even with zero inflation, because the money is available earlier for reinvestment.

The cost or value of money must also be considered. When borrowing money, a percentage fee or interest rate must normally be paid. However, the interest rate may not necessarily be the correct cost of money to use in an economic analysis. Another factor, called the **discount rate**, is more commonly used to reflect the true cost of money [see Fuller and Petersen (1996) for detailed discussions]. Discount rates used for analyses vary depending on individual investment, profit, and other opportunities. Interest rates, in contrast, tend to be more centrally fixed by lending institutions.

To minimize the confusion caused by the vague definition and variable nature of discount rates, the U.S. government has specified particular discount rates to be used in economic analyses relating to federal expenditures. These discount rates are updated annually (Schultz, Rushing and Fuller 2004) but may not be appropriate for private-sector economic analyses.

Periodic Costs

Regularly or periodically recurring costs include insurance, property taxes, income taxes, rent, refurbishment expenses, disposal fees (e.g., refrigerant recycling costs), occasional major repair costs, and decommissioning expenses.

Insurance. Insurance reimburses a property owner for a financial loss so that equipment can be repaired or replaced. Insurance often indemnifies the owner from liability, as well. Financial recovery may include replacing income, rents, or profits lost due to property damage.

Some of the principal factors that influence the total annual insurance premium are building size, construction materials, amount and size of mechanical equipment, geographic location, and policy deductibles. Some regulations set minimum required insurance coverage and premiums that may be charged for various forms of insurable property.

Property Taxes. Property taxes differ widely and may be collected by one or more agencies, such as state, county, or local governments or special assessment districts. Furthermore, property taxes may apply to both real (land, buildings) and personal (everything else) property. Property taxes are most often calculated as a percentage of assessed value but are also determined in other ways, such as fixed fees, license fees, registration fees, etc. Moreover, definitions of assessed value vary widely in different geographic areas. Tax experts should be consulted for applicable practices in a given area.

Income Taxes. Taxes are generally imposed in proportion to net income, after allowance for expenses, depreciation, and numerous other factors. Special tax treatment is often granted to encourage certain investments. Income tax professionals can provide up-to-date information on income tax treatments.

Other Periodic Costs. Examples of other costs include changes in regulations that require unscheduled equipment refurbishment to eliminate use of hazardous substances, and disposal costs for such substances.

Replacement Costs and Salvage Value. Replacement costs and salvage value should be evaluated when calculating owning cost. Replacement cost is the cost to remove existing equipment and install new equipment. Salvage value is the value of equipment or its components for recycling or other uses. Equipment's salvage value may be negative when removal, disposal, or decommissioning costs are considered.

OPERATING COSTS

Operating costs are those incurred by the actual operation of the system. They include costs of fuel and electricity, wages, supplies, water, material, and maintenance parts and services. Energy is a

large part of total operating costs. Chapter 32 of the 2005 *ASHRAE Handbook—Fundamentals* outlines how fuel and electrical requirements are estimated. Because most energy management activities are dictated by economics, the facility manager must understand the utility rates that apply to each facility. Electric rates are usually more complex than gas or water rates. In addition to general commercial or institutional electric rates, special rates may exist such as time of day, interruptible service, on-peak/off-peak, summer/winter, and peak demand. Electric rate schedules vary widely in North America. The facility manager should work with local utility companies to identify the most favorable rates and to understand how to qualify for them. The local utility representative can help the facility manager develop the most cost-effective methods of metering and billing. The facility manager must understand the utility rates, including the distinction between marginal and average costs and, in the case of demand-based electric rates, how demand is computed.

Note that, in general, total energy consumption cannot be multiplied by a per-unit energy cost to arrive at a correct annual utility cost, because rate schedules (especially for electricity), often have a sliding scale of prices that vary with consumption, time of day, and other factors.

Future energy costs used in discounted payback analyses must be carefully evaluated. Energy costs have historically escalated at a different rate than the overall inflation rate as measured by the consumer price index. To assist in life-cycle cost analysis, fuel price escalation rate forecasts, by end-use sector and fuel type, are updated annually by the National Institute of Standards and Technology, and published in the Annual Supplement to NIST *Handbook* 135 (Schultz et al. 2004). Future natural gas prices are also forecast by the Gas Research Institute and published annually (GRI 2000). There are no published projection rates for water prices to be used in life-cycle cost analyses. Water escalation rates should be obtained from the local water utility when possible. Building designers should use energy price projections from their local utility in place of regional forecasts whenever possible, especially when evaluating alternative fuel types.

Deregulation in some areas may allow increased access to nontraditional energy providers and pricing structures; in other areas, traditional utility infrastructures and practices may prevail. The amount and profile of the energy used by the facility will also determine energy cost. Unbundling energy services (having separate contracts for energy and for its transportation to point of use) may dictate separate agreements for each service component or may be packaged by a single provider. Contract length and price stability are factors in assessing nontraditional versus traditional energy suppliers when estimating operating costs. The degree of energy supply and system reliability and price stability considered necessary by the owner/occupants of a building may require considerable deliberation. The sensitivity of a building's functionality to energy-related variables should dictate the degree of attention allocated in evaluating these factors.

Electrical Energy

The total cost of electricity is determined by a rate schedule and is usually a combination of several components: consumption (kilowatt-hours), demand (kilowatts) fuel adjustment charges, special allowances or other adjustments, and applicable taxes. Of these, consumption and demand are the major cost components and the ones the owner or facility manager may be able to affect.

Electricity Consumption Charges. Most electric rates have step-rate schedules for consumption, and the cost of the last unit consumed may be substantially different from that of the first. The last unit is usually cheaper than the first because the fixed costs to the utility may already have been recovered from earlier consumption costs. Because of this, the energy analysis cannot use average costs to accurately predict savings from implementation of energy conservation measures. Average costs will overstate the savings

possible between alternative equipment or systems; instead, marginal (or incremental) costs must be used.

To reflect time-varying operating costs or to encourage peak shifting, electric utilities may charge different rates for consumption according to the time of use and season, with higher costs occurring during the peak period of use.

Fuel Adjustment Charge. Because of substantial variations in fuel prices, electric utilities may apply a fuel adjustment charge to recover costs. This adjustment may not be reflected in the rate schedule. The fuel adjustment is usually a charge per unit of consumption and may be positive or negative, depending on how much of the actual fuel cost is recovered in the energy consumption rate. The charge may vary monthly or seasonally.

Allowances or Adjustments. Special discounts or rates may be available for customers who can receive power at higher voltages or for those who own transformers or similar equipment. Special rates or riders may be available for specific interruptible loads such as domestic water heaters.

Certain facility electrical systems may produce a low power factor [i.e., ratio of real (active) kilowatt power to apparent (reactive) kVA power], which means that the utility must supply more current on an intermittent basis, thus increasing their costs. These costs may be passed on as an adjustment to the utility bill if the power factor is below a level established by the utility.

When calculating power bills, utilities should be asked to provide detailed cost estimates for various consumption levels. The final calculation should include any applicable special rates, allowances, taxes, and fuel adjustment charges.

Demand Charges. Electric rates may also have demand charges based on the customer's peak kilowatt demand. Whereas consumption charges typically cover the utility's operating costs, demand charges typically cover the owning costs.

Demand charges may be formulated in a variety of ways:

- *Straight charge*. Cost per kilowatt per month, charged for the peak demand of the month.
- *Excess charge*. Cost per kilowatt above a base demand (e.g., 50 kW), which may be established each month.
- *Maximum demand (ratchet)*. Cost per kilowatt for maximum annual demand, which may be reset only once a year. This established demand may either benefit or penalize the owner.
- *Combination demand*. Cost per hour of operation of demand. In addition to a basic demand charge, utilities may include further demand charges as demand-related consumption charges.

    The actual demand represents the peak energy use averaged over a specific period, usually 15, 30, or 60 min. Accordingly, high electrical loads of only a few minutes' duration may never be recorded at the full instantaneous value. Alternatively, peak demand is recorded as the average of several consecutive short periods (i.e., 5 min out of each hour).

    The particular method of demand metering and billing is important when load shedding or shifting devices are considered. The portion of the total bill attributed to demand may vary greatly, from 0% to as high as 70%.

- *Real-time* or *time-of-day rates*. Cost of electricity at time of use. An increasing number of utilities offer these rates. End users who can shift operations or install electric load-shifting equipment, such as thermal storage, can take advantage of such rates. Because these rates usually reflect a utility's overall load profile and possibly the availability of specific generating resources, contact with the supplying utility is essential to determine whether these rates are a reasonable option for a specific application.

Understanding Electric Rates. To illustrate a typical commercial electric rate with a ratchet, electricity consumption and demand data for an example building are presented in Table 5.

Table 5 Electricity Data Consumption and Demand for Atlanta Example Building, 2003 to 2004

	Billing Days	Consumption, kWh	Actual Demand, kW	Billing Demand, kW	Total Cost, US$
Jan. 2003	29	57,120	178	185	4,118
Feb. 2003	31	61,920	145	185	4,251
Mar. 2003	29	60,060	140	185	4,199
Apr. 2003	29	62,640	154	185	4,271
May. 2003	33	73,440	161	185	4,569
Jun. 2003	26	53,100	171	185	4,007
Jul. 2003	32	67,320	180	185	4,400
Aug. 2003	30	66,000	170	185	4,364
Sep. 2003	32	63,960	149	171	4,127
Oct. 2003	30	55,260	122	171	3,865
Nov. 2003	27	46,020	140	171	3,613
Dec. 2003	34	61,260	141	171	4,028
Total 2003	**362**	**670,980**			**49,812**
Jan. 2004	31	59,040	145	171	3,967
Feb. 2004	29	54,240	159	171	3,837
Mar. 2004	20	37,080	122	171	2,584
Apr. 2004	12	22,140	133	171	1,547
May. 2004	34	64,260	148	171	4,110
Jun. 2004	29	63,720	148	171	4,321
Jul. 2004	30	69,120	169	169	4,458
Aug. 2004	32	73,800	170	170	4,605
Sep. 2004	29	64,500	166	166	4,281
Oct. 2004	30	60,060	152	161	3,866
Nov. 2004	32	65,760	128	161	4,018
Dec. 2004	31	51,960	132	161	3,646
Total 2004	**339**	**685,680**			**45,240**
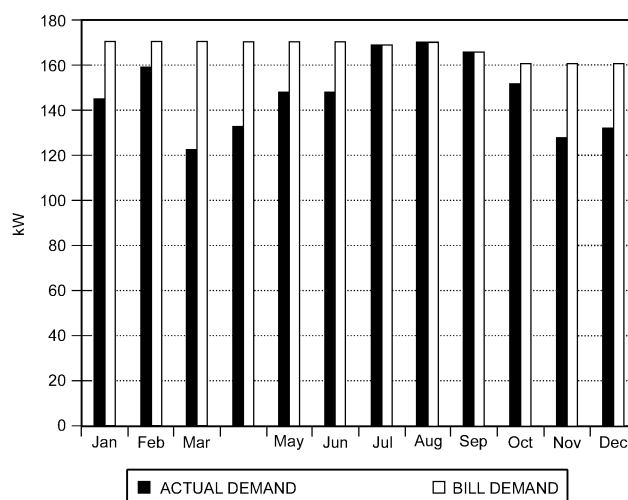
Fig. 2   Bill Demand and Actual Demand for Atlanta Example Building, 2004

The example building in Table 5 is on a ratcheted rate, and bill demand is determined as a percentage of actual demand in the summer. How the ratchet operates is illustrated in Figure 2.

Table 5 shows that the actual demand in the first six months of 2004 had no effect on the billing demand, and therefore no effect on the dollar amount of the bill. The same is true for the last three months of the year. Because of the ratchet, the billing demand in the first half of 2004 was set the previous summer. Likewise, billing demand for the last half of 2004 and first half of 2005 was set by the peak actual demand of 180 kW in July 2003. This tells the facility manager to pay attention to demand in the summer months (June to

September) and that demand is not a factor in the winter (October to May) and facility months for this particular rate. (Note that the Atlanta building is in a hot, humid climate; in other climates, winter electric demand is an important determinant of costs.) Consumption must be monitored all year long.

Understanding the electric rates is key when evaluating the economics of energy conservation projects. Some projects save electrical demand but not consumption; others save mostly consumption but have little effect on demand. Electric rates must be correctly applied for economic analyses to be accurate. Chapter 55 contains a thorough discussion of various electric rates.

Natural Gas

Rates. Conventional natural gas rates are usually a combination of two main components: (1) utility rate or base charges for gas consumption and (2) purchased gas adjustment (PGA) charges.

Although gas is usually metered by volume, it is often sold by energy content. The utility rate is the amount the local distribution company charges per unit of energy to deliver the gas to a particular location. This rate may be graduated in steps; the first 100 units of gas consumed may not be the same price as the last 100 units. The PGA is an adjustment for the cost of the gas per unit of energy to the local utility. It is similar to the electric fuel adjustment charge. The total cost per unit is then the sum of the appropriate utility rate and the PGA, plus taxes and other adjustments.

Interruptible Gas Rates and Contract/Transport Gas. Large industrial plants usually have the ability to burn alternative fuels and can qualify for special interruptible gas rates. During peak periods of severe cold weather, these customers' supply may be curtailed by the gas utility, and they may have to switch to propane, fuel oil, or some other backup fuel. The utility rate and PGA are usually considerably cheaper for these interruptible customers than they are for firm-rate (noninterruptible) customers.

Deregulation of the natural gas industry allows end users to negotiate for gas supplies on the open market. The customer actually contracts with a gas producer or broker and pays for the gas at the source. Transport fees must be negotiated with the pipeline companies carrying the gas to the customer's local gas utility. This can be a very complicated administrative process and is usually economically feasible only for large gas users. Some local utilities have special rates for delivering contract gas volumes through their system; others simply charge a standard utility fee (PGA is not applied because the customer has already negotiated with the supplier for the cost of the fuel itself).

When calculating natural gas bills, be sure to determine which utility rate and PGA and/or contract gas price is appropriate for the particular interruptible or firm-rate customer. As with electric bills, the final calculation should include any taxes, prompt payment discounts, or other applicable adjustments.

Other Fossil Fuels

Propane, fuel oil, and diesel are examples of other fossil fuels in widespread use. Calculating the cost of these fuels is usually much simpler than calculating typical utility rates.

The cost of the fuel itself is usually a simple charge per unit volume or per unit mass. The customer is free to negotiate for the best price. However, trucking or delivery fees must also be included in final calculations. Some customers may have their own transport trucks, but most seek the best delivered price. If storage tanks are not customer-owned, rental fees must be considered. Periodic replacement of diesel-type fuels may be necessary because of storage or shelf-life limitations and must also be considered. The final fuel cost calculation should include any of these costs that are applicable, as well as appropriate taxes.

It is usually difficult, however, to relate usage of stored fossil fuels (e.g., fuel oil) with their operating costs. This is because propane or fuel oil is bought in bulk and stored until needed, and nor-

mally not metered or measured as it is consumed, whereas natural gas and power are metered and billed for as they are used.

Energy Source Choices

In planning for a new facility, the designer may undertake **energy master planning**. One component of energy master planning is choice of fuels. Typical necessary decisions include, for example, whether the building should be heated by electricity or natural gas, how service hot water should be produced, whether a hybrid heating plant (i.e., a combination of both electric and gas boilers) should be considered, and whether emergency generators should be fueled by diesel or natural gas.

Decision makers should consider histories or forecasts of price volatility when selecting energy sources. In addition to national trending, local energy price trends from energy suppliers can be informative. These evaluations are particularly important where relative operating costs parity exists between various fuel options, or where selecting more efficient equipment may help mitigate utility price concerns.

Many sources of historic and projected energy costs are available for reference. In addition to federal projections, utility and energy supplier annual reports and accompanying financial data may provide insight into future energy costs. Indicators such as constrained or declining energy supply or production may be key factors in projecting future energy pricing trends. Pricing patterns that suggest unusual levels of energy price volatility should be carefully analyzed and tested at extreme predicted price levels to assess potential effects on system operating costs.

Under conditions of rapidly evolving energy prices or new pricing options, imminent technological improvements, or pending environmental standards and mandates, the adaptability of design options must be carefully evaluated. Where appropriate, contingency planning for accommodating foreseeable alterations to building systems may be prudent. Using diverse energy sources or suppliers in lieu of single sourcing may reduce cost of shifting energy use in the event that single-source pricing becomes volatile, and may even provide negotiating leverage for facility owners.

Water and Sewer Costs

Water and sewer costs have risen in many parts of the country, and should not be overlooked in economic analyses. Fortunately, these rates are usually very simple and straightforward: commonly, a charge per hundred cubic feet (CCF) for water and a different charge per CCF for sewer. Because water consumption is metered while sewage is not, most rates use the water consumption quantity to compute the sewer charge. If an owner uses water that is not returned to sewer, there may be an opportunity to receive a credit or refund. Owners frequently use irrigation meters for watering grounds when the water authority has a special irrigation rate with no sewer charge. Another opportunity that is sometimes overlooked is to separately meter makeup water for cooling towers. This can be done with an irrigation meter if the costs of setting the meter can be justified; alternatively, it may be done by installing an in-line water meter for the cooling tower, in which case the owner reports the usage annually and applies for a credit or refund.

Because of rising costs of water and sewer, water recycling and reclamation is becoming more cost effective. For example, it may now be cost effective in some circumstances to capture cooling coil condensate and pump it to a cooling tower for makeup water.

MAINTENANCE COSTS

The quality of maintenance and maintenance supervision can be a major factor in overall life-cycle cost of a mechanical system. The maintenance cost of mechanical systems varies widely depending upon configuration, equipment locations, accessibility, system complexity, service duty, geography, and system reliability requirements.

Table 6 Comparison of Maintenance Costs Between Studies

Survey	Cost per ft², as Reported		Consumer Price Index	Cost per ft², 2004 Dollars	
	Mean	Median		Mean	Median
Dohrmann and Alereza (1983)	$0.32	$0.24	99.6	$0.61	$0.46
Abramson et al. (2005)	$0.47	$0.44	188.9	$0.47	$0.44

Maintenance costs can be difficult to predict, because system and facility are unique.

Dohrmann and Alereza (1986) obtained maintenance costs and HVAC system information from 342 buildings located in 35 states in the United States. In 1983 U.S. dollars, data collected showed a mean HVAC system maintenance cost of $0.32/ft² per year, with a median cost of $0.24/ft² per year. Building age has a statistically significant but minor effect on HVAC maintenance costs. Analysis also indicated that building size is not statistically significant in explaining cost variation. The type of maintenance program or service agency that building management chooses can also have a significant effect on total HVAC maintenance costs. Although extensive or thorough routine and preventive maintenance programs cost more to administer, they usually extend equipment life; improve reliability; and reduce system downtime, energy costs, and overall life-cycle costs.

Some maintenance cost data are available, both in the public domain and from proprietary sources used by various commercial service providers. These sources may include equipment manufacturers, independent service providers, insurers, government agencies (e.g., the General Services Administration), and industry-related organizations [e.g., the Building Owners and Managers Association (BOMA)] and service industry publications. More traditional, widely used products and components are likely to have statistically reliable records. However, design changes or modifications necessitated by industry changes, such as alternative refrigerants, may make historical data less relevant.

Newer HVAC products, components, system configurations, control systems and protocols, and upgraded or revised system applications present an additional challenge. Care is required when using data not drawn from broad experience or field reports. In many cases, the maintenance information is proprietary or was sponsored by a particular entity or group. Particular care should be taken when using such data. It is the user's responsibility to obtain these data and to determine their appropriateness and suitability for the application being considered.

ASHRAE Research Project TRP-1237 (Abramson et al. 2005) developed a standardized internet-based data collection tool and database on HVAC equipment service life and maintenance costs. The database was seeded with data on 163 buildings from around the country. Maintenance cost data were gathered for total HVAC system maintenance costs from 100 facilities. In 2004 dollars, the mean HVAC maintenance cost from these data was $0.47/ft², and the median cost was $0.44/ft². Table 6 compares these figures with estimates reported by Dohrmann and Alereza (1983), both in terms of contemporary dollars, and in 2004 dollars, and shows that the cost per square foot varies widely between studies.

Estimating Maintenance Costs

Total HVAC maintenance cost for new and existing buildings with various types of equipment may be estimated several ways, using several resources. Equipment maintenance requirements can be obtained from the equipment manufacturers for large or custom pieces of equipment. Estimating in-house labor requirements can be difficult; BOMA (2003) provides guidance on this topic. Many independent mechanical service companies provide preventative maintenance contracts. These firms typically have proprietary esti-

mating programs developed through their experience, and often provide generalized maintenance costs to engineers and owners upon request, without obligation.

When evaluating various HVAC systems during design or retrofit, the absolute magnitude of maintenance costs may not be as important as the relative costs. Whichever estimating method or resource is selected, it should be used consistently throughout any evaluation. Mixing information from different resources in an evaluation may provide erroneous results.

Applying simple costs per unit of building floor area for maintenance is highly discouraged. Maintenance costs can be generalized by system types. When projecting maintenance costs for different HVAC systems, the major system components need to be identified with a required level of maintenance. The potential long-term costs of environmental issues on maintenance costs should also be considered.

Factors Affecting Maintenance Costs

Maintenance costs are primarily a measure of labor activity. System design, layout, and configuration can significantly affect the amount of time and effort required for maintenance and, therefore, the maintenance cost. Factors to consider when evaluating maintenance costs include the following:

- **Quantity and type of equipment.** Each piece of equipment requires a core amount of maintenance and time, regardless of its size or capacity. A greater number of similar pieces of equipment are generally more expensive to maintain than larger but fewer units. For example, one manufacturer suggests the annual maintenance for centrifugal chillers is 24 h for a nominal 1000 ton chiller and 16 h for a nominal 500 ton chiller. Therefore, the total maintenance labor for a 1000 ton chiller plant with two 500 ton chillers would be 32 h, or 1/3 more than a single 1000 ton chiller.

- **Equipment location and access.** The ability to maintain equipment in a repeatable and cost-effective manner is significantly affected by the equipment's location and accessibility. Equipment that is difficult to access increases the amount of time required to maintain it, and therefore increases maintenance cost. Equipment maintenance requiring erection of ladders and scaffolding or hydraulic lifts increases maintenance costs while likely reducing the quantity and quality of maintenance performed. Equipment location may also dictate an unusual working condition that could require more service personnel than normal. For example, maintenance performed in a confined space (per OSHA definitions) requires an additional person to be present, for safety reasons.

- **System run time.** The number of hours of operation for a HVAC system affects maintenance costs. Many maintenance tasks are dictated by equipment run time. The greater the run time, the more often these tasks need to be performed.

- **Critical systems.** High-reliability systems require more maintenance to ensure uninterrupted system operation. Critical system maintenance is also usually performed with stringent shutdown and failsafe procedures that tend to increase the amount of time required to service equipment. An office building system can be turned off for a short time with little effect on occupants, allowing maintenance almost any time. Shutdown of a hospital operating room or pharmaceutical manufacturing HVAC system, on the other hand, must be coordinated closely with the operation of the facility to eliminate risk to patients or product. Maintenance on critical systems may sometimes incur labor premiums because of unusual shutdown requirements.

- **System complexity.** More complex systems tend to involve more equipment and sophisticated controls. Highly sophisticated systems may require highly skilled service personnel, who tend to be more costly.

- **Service environment.** HVAC systems subjected to harsh operating conditions (e.g., coastal and marine environments) or environ-

ments like industrial operations may require more frequent and/or additional maintenance.

- **Local conditions.** The physical location of the facility may require additional maintenance. Equipment in dusty or dirty areas or exposed to seasonal conditions (e.g., high pollen, leaves) may require more frequent or more difficult cleaning of equipment and filters. Additional maintenance tasks may be needed.

- **Geographical location.** Maintenance costs for remote locations must consider the cost of getting to and from the locations. Labor costs for the number of anticipated trips and their duration for either in-house or outsourced service personnel to travel to and from the site must be added to the maintenance cost to properly estimate the total maintenance cost.

- **Equipment age.** The effect of age on equipment repair costs varies significantly by type of HVAC equipment. Significant technology changes in equipment design and application have occurred that affect maintenance costs.

- **Available infrastructure.** Maintenance costs are affected by the availability of an infrastructure that can maintain equipment, components, and systems. Available infrastructure varies on a national, regional, and local basis and is an important consideration in the HVAC system selection process.

REFRIGERANT PHASEOUTS

The production phaseout of many commonly used refrigerants has required building owners to decide between, replacing existing equipment or retrofitting for alternative refrigerants. Several factors must be considered, including

- **Initial Cost.** New equipment may have a significantly higher installed cost than retrofitting existing equipment. For example, the retrofit of an existing centrifugal chiller to operate on R-123 may cost 50% of the cost for a new chiller, making the installation cost of a new chiller seem a prudent alternative. Conversely, the cost of rigging a new unit may significantly raise the installed cost, improving the first-cost advantage of refrigerant conversion.

- **Operating Costs.** The overall efficiency of new equipment is often substantially better than that of existing equipment, depending on age, usage, and level of maintenance performed over the life of the existing unit. In addition, conversion to alternative refrigerants may reduce capacity and/or efficiency of the existing equipment.

- **Maintenance Costs.** The maintenance cost for new equipment is generally lower than that for existing equipment. However, the level of retrofit required to attain compatibility between existing equipment and new refrigerant often includes replacement or remanufacture of major unit components, which can bring the maintenance and repair costs in line with those expected of new equipment.

- **Equipment Useful Life.** The impact of a retrofit on equipment useful life is determined by the extent of modification required. The complete remanufacture of a unit should extend the remaining useful life to a level comparable to that of new equipment.

Replacing existing equipment or converting to alternative refrigerants can improve overall system efficiency. Reduced capacity requirements and introduction of new technologies such as variable-speed drives and microprocessor-based controllers can substantially reduce annual operating costs and significantly improve a project's economic benefit.

Information should be gathered to complete Table 1 for each alternative. The techniques described in the section on Economic Analysis Techniques may then be applied to compare the relative values of each option.

Other Sources

The DOE's Federal Energy Management Program (FEMP) Web site (www.eere.energy.gov/femp/procurement) has up-to-date information on energy-efficient federal procurement. Products that qualify for the EPA/DOE ENERGY STAR label are listed, as are efficiency recommendations, cost effectiveness examples, and purchasing guidance. FEMP also provides web-based cost-calculator tools that simplify the energy cost comparison between products with different efficiencies.

The General Services Administration (GSA) has a basic ordering agreement (BOA) that offers a streamlined procurement method for some HVAC products based on lowest life-cycle cost. For chillers purchased through commercial sources, the BOA can still be used as a guide in preparing specifications.

OTHER ISSUES

Financing Alternatives

Alternative financing is commonly used in third-party funding of projects, particularly retrofit projects, and is variously called privatization, third-party financing, energy services outsourcing, performance contracting, energy savings performance contracting (ESPC), or innovative financing. In these programs, an outside party performs an energy study to identify or quantify attractive energy-saving retrofit projects and then (to varying degrees) designs, builds, and finances the retrofit program on behalf of the owner or host facility. These contracts range in complexity from simple projects such as lighting upgrades to more detailed projects involving all aspects of energy consumption and facility operation.

Alternative financing can be used to accomplish any or all of the following objectives:

- Upgrade capital equipment
- Provide for maintenance of existing facilities
- Speed project implementation
- Conserve or defer capital outlay
- Save energy
- Save money

The benefits of alternative financing are not free. In general terms, these financing agreements transfer the risk of attaining future savings from the owner to the contractor, for which the contractor is paid. In addition, these innovative owning and operating cost reduction approaches have important tax consequences that should be investigated on a case-by-case basis.

There are many variations of the basic arrangements and nearly as many terms to define them. Common nomenclature includes guaranteed savings (performance-based), shared savings, paid from savings, guaranteed savings loans, capital leases, municipal leases, and operating leases. For more information, refer to the U.S. Department of Energy's Web site and to the DOE (2007). A few examples of alternative financing techniques follow.

Leasing. Among the most common methods of alternative financing is the lease arrangement. In a true lease or lease-purchase arrangement, outside financing provides capital for construction of a facility. The institution then leases the facility at a fixed monthly charge and assumes responsibility for fuel and personnel costs associated with its operation. Leasing is also commonly available for individual pieces of equipment or retrofit systems and often includes all design and installation costs. Equipment suppliers or independent third parties retain ownership of new equipment and lease it to the user.

Outsourcing. For a cogeneration, steam, or chilled-water plant, either a lease or an energy output contract can be used. An energy output contract enables a private company to provide all the capital and operating costs, such as personnel and fuel, while the host facil-

ity purchases energy from the operating company at a variable monthly charge.

Energy Savings. Retrofit projects that lower energy usage create an income stream that can be used to amortize the investment. In **paid-from-savings** programs, utility payments remain constant over a period of years while the contractor is paid out of savings until the project is amortized. In **shared savings** programs, the institution receives a percentage of savings over a longer period of years until the project becomes its property. In a **guaranteed savings** program, the owner retains all the savings and is guaranteed that a certain level of savings will be attained. A portion of the savings is used to amortize the project. In any type of energy savings project, building operation and use can strongly affect the amount of savings actually realized.

Low-Interest Financing. In this arrangement, the supplier offers equipment with special financing arrangements at below-market interest rates.

Cost Sharing. Several variations of cost-sharing programs exist. In some instances, two or more groups jointly purchase and share new equipment or facilities, thereby increasing use of the equipment and improving the economic benefits for both parties. In other cases, equipment suppliers or independent third parties (such as utilities) who receive an indirect benefit may share part of the equipment or project cost to establish a market foothold for the product.

District Energy Service

District energy service is increasingly available to building owners; district heating and cooling eliminates most on-site heating and cooling equipment. A third party produces treated water or steam and pipes it from a central plant directly to the building. The building owner then pays a metered rate for the energy that is used.

A cost comparison of district energy service versus on-site generation requires careful examination of numerous, often site-specific, factors extending beyond demand and energy charges for fuel. District heating and cooling eliminates or minimizes most costs associated with installation, maintenance, administration, repair and operation of on-site heating and cooling equipment. Specifically, costs associated with providing water, water treatment, specialized maintenance services, insurance, staff time, space to house on-site equipment, and structural additions needed to support equipment should be considered. Costs associated with auxiliary equipment, which represent 20 to 30% of the total plant annual operating costs, should also be included.

Any analysis that fails to include all the associated costs does not give a clear picture of the building owner's heating and cooling alternatives. In addition to the tangible costs, there are a number of other factors that should be considered, such as convenience, risk, environmental issues, flexibility, and backup.

On-Site Electrical Power Generation

On-site electrical power generation covers a broad range of applications, from emergency back-up to power for a single piece of equipment to an on-site power plant supplying 100% of the facility's electrical power needs. Various system types and fuel sources are available, but the economic principles described in this chapter apply equally to all of them. Other chapters (e.g., Chapters 7 and 33 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*) may be helpful in describing system details.

An economic study of on-site electrical power generation should include consideration of all owning, operating, and maintenance costs. Typically, on-site generation is capital intensive (i.e., high first cost) and therefore requires a high use rate to produce savings adequate to support the investment. High use rates mean high run time, which requires planned maintenance and careful operation.

Owning costs include any related systems required to adapt the building to on-site power generation. Additional equipment is required if the building will also use purchased power from a utility.

Costs associated with shared equipment should also be considered. For example, if the power source for the generator is a steam turbine, and a hot-water boiler would otherwise be used to meet the HVAC demand, the boiler would need to be a larger, high-pressure steam boiler with a heat exchanger to meet the hot-water needs. Operation and maintenance costs for the boiler also are increased because of the increased operating hours.

Costs of an initial investment and ongoing inventory of spare parts must also be considered. Most equipment manufacturers provide a recommended spare parts list as well as recommended maintenance schedules, typically daily, weekly, and monthly routine maintenance and periodic major overhauls. Major overhaul frequency depends on equipment use and requires taking the equipment off-line. The cost of either lost building use or the provision of electricity from an alternative source during the shutdown should be considered.

ECONOMIC ANALYSIS TECHNIQUES

Analysis of overall owning and operating costs and comparisons of alternatives require an understanding of the cost of lost opportunities, inflation, and the time value of money. This process of economic analysis of alternatives falls into two general categories: simple payback analysis and detailed economic analyses (life-cycle cost analyses).

A simple payback analysis reveals options that have short versus long paybacks. Often, however, alternatives are similar and have similar paybacks. For a more accurate comparison, a more comprehensive economic analysis is warranted. Many times it is appropriate to have both a simple payback analysis and a detailed economic analysis. The simple payback analysis shows which options should not be considered further, and the detailed economic analysis determines which of the viable options are the strongest. The strongest options can be accepted or further analyzed if they include competing alternatives.

Simple Payback

In the simple payback technique, a projection of the revenue stream, cost savings, and other factors is estimated and compared to the initial capital outlay. This simple technique ignores the cost of borrowing money (interest) and lost opportunity costs. It also ignores inflation and the time value of money.

Example 1. Equipment item 1 costs $10,000 and will save $2000 per year in operating costs; equipment item 2 costs $12,000 and saves $3000 per year. Which item has the best simple payback?

Item 1 $10,000/($2000/yr) = 5-year simple payback

Item 2 $12,000/($3000/yr) = 4-year simple payback

Because analysis of equipment for the duration of its realistic life can produce a very different result, the simple payback technique should be used with caution.

More Sophisticated Economic Analysis Methods

Economic analysis should consider details of both positive and negative costs over the analysis period, such as varying inflation rates, capital and interest costs, salvage costs, replacement costs, interest deductions, depreciation allowances, taxes, tax credits, mortgage payments, and all other costs associated with a particular system. See the section on Symbols for definitions of variables.

Present-Value (Present Worth) Analysis. All sophisticated economic analysis methods use the basic principles of present value analysis to account for the time value of money. Therefore, a good understanding of these principles is important.

The total present value (present worth) for any analysis is determined by summing the present worths of all individual items under

consideration, both future single-payment items and series of equal future payments. The scenario with the highest present value is the preferred alternative.

Single-Payment Present-Value Analysis. The cost or value of money is a function of the available interest rate and inflation rate. The future value F of a present sum of money P over n periods with compound interest rate i per period is

$$F = P(1 + i)^n \tag{1}$$

Conversely, the present value or present worth P of a future sum of money F is given by

$$P = F/(1 + i)^n \tag{2}$$

or

$$P = F \times \text{PWF}(i,n)_{sgl} \tag{3}$$

where the single-payment present-worth factor $\text{PWF}(i,n)_{sgl}$ is defined as

$$\text{PWF}(i,n)_{sgl} = 1/(1 + i)^n \tag{4}$$

Example 2. Calculate the value in 10 years at 10% per year interest of a system presently valued at $10,000.

$$F = P(1 + i)^n = \$10,000(1 + 0.1)^{10} = \$25,937.42$$

Example 3. Using the present-worth factor for 10% per year interest and an analysis period of 10 years, calculate the present value of a future sum of money valued at $10,000. (Stated another way, determine what sum of money must be invested today at 10% per year interest to yield $10,000 10 years from now.)

$$P = F \times \text{PWF}(i,n)_{sgl}$$

$$P = \$10,000 \times 1/(1 + 0.1)^{10}$$

$$= \$3855.43$$

Series of Equal Payments. The present-worth factor for a series of future equal payments (e.g., operating costs) is given by

$$\text{PWF}(i,n)_{ser} = \frac{(1 + i)^n - 1}{i(1 + i)^n} \tag{5}$$

The present value P of those future equal payments (PMT) is then the product of the present-worth factor and the payment [i.e., $P = \text{PWF}(i,n)_{ser} \times \text{PMT}$].

The number of future equal payments to repay a present value of money is determined by the capital recovery factor (CRF), which is the reciprocal of the present-worth factor for a series of equal payments:

$$\text{CRF} = \text{PMT}/P \tag{6}$$

$$\text{CRF}(i,n) = \frac{i(1 + i)^n}{(1 + i)^n - 1} = \frac{i}{1 - (1 + i)^{-n}} \tag{7}$$

The CRF is often used to describe periodic uniform mortgage or loan payments.

Note that when payment periods other than annual are to be studied, the interest rate must be expressed per appropriate period. For example, if monthly payments or return on investment are being analyzed, then interest must be expressed per month, not per year, and n must be expressed in months.

Example 4. Determine the present value of an annual operating cost of $1000 per year over 10 years, assuming 10% per year interest rate.

$$\text{PWF}(i,n)_{ser} = [(1 + 0.1)^{10} - 1]/[0.1(1 + 0.1)^{10}] = 6.14$$

$$P = \$1000(6.14) = \$6140$$

Example 5. Determine the uniform monthly mortgage payments for a loan of $100,000 to be repaid over 30 years at 10% per year interest. Because the payment period is monthly, the payback duration is $30(12) = 360$ monthly periods, and the interest rate per period is $0.1/12 = 0.00833$ per month.

$$\text{CRF}(i,n) = 0.00833(1 + 0.00833)^{360}/[(1 + 0.00833)^{360} - 1]$$

$$= 0.008773$$

$$\text{PMT} = P(\text{CRF})$$

$$= \$100,000(0.008773)$$

$$= \$877.30 \text{ per month}$$

Improved Payback Analysis. This somewhat more sophisticated payback approach is similar to the simple payback method, except that the cost of money (interest rate, discount rate, etc.) is considered. Solving Equation (7) for n yields the following:

$$n = \frac{\ln[\text{CRF}/(\text{CRF} - i)]}{\ln(1 + i)} \tag{8}$$

Given known investment amounts and earnings, CRFs can be calculated for the alternative investments. Subsequently, the number of periods until payback has been achieved can be calculated using Equation (8).

Example 6. Compare the years to payback of the same items described in Example 2 if the value of money is 10% per year.

Item 1

$$\begin{aligned}
\text{cost} &= \$10,000 \\
\text{savings} &= \$2000/\text{year} \\
\text{CRF} &= \$2000/\$10,000 = 0.2 \\
n &= \ln[0.2/(0.2 - 0.1)]/\ln(1 + 0.1) = 7.3 \text{ years}
\end{aligned}$$

Item 2

$$\begin{aligned}
\text{cost} &= \$12,000 \\
\text{savings} &= \$3000/\text{year} \\
\text{CRF} &= \$3000/\$12,000 = 0.25 \\
n &= \ln[0.25/(0.25 - 0.1)]/\ln(1 + 0.1) = 5.4 \text{ years}
\end{aligned}$$

If years to payback is the sole criteria for comparison, Item 2 is preferable because the investment is repaid in a shorter period of time.

Accounting for Inflation. Different economic goods may inflate at different rates. Inflation reflects the rise in the real cost of a commodity over time and is separate from the time value of money. Inflation must often be accounted for in an economic evaluation. One way to account for inflation is to substitute effective interest rates that account for inflation into the equations given in this chapter.

The effective interest rate i', sometimes called the real rate, accounts for inflation rate j and interest rate i or discount rate i_d; it can be expressed as follows (Kreider and Kreith 1982):

$$i' = \frac{1 + i}{1 + j} - 1 = \frac{i - j}{1 + j} \tag{9}$$

Different effective interest rates can be applied to individual components of cost. Projections for future fuel and energy prices are available in the *Annual Supplement to NIST Handbook* 135 (Schultz et al. 2004).

Example 7. Determine the present worth P of an annual operating cost of $1000 over 10 years, given a discount rate of 10% per year and an inflation rate of 5% per year.

$$i' = (0.1 - 0.05)/(1 + 0.05) = 0.0476$$

$$\text{PWF}(i',n)_{ser} = \frac{(1 + 0.0476)^{10} - 1}{0.0476(1 + 0.0476)^{10}} = 7.813$$

$$P = \$1000(7.813) = \$7813$$

The following are three common methods of present-value analysis that include life-cycle cost factors (life of equipment, analysis period, discount rate, energy escalation rates, maintenance cost, etc., as shown in Table 1). These comparison techniques rely on the same assumptions and economic analysis theories but display the results in different forms. They also use the same definition of each term. All can be displayed as a single calculation or as a cash flow table using a series of calculations for each year of the analysis period.

Savings-to-Investment Ratio. Most large military-sponsored work and many other U.S. government entities require a savings-to-investment-ratio (SIR) method. This method produces a ratio that defines the relative economic strength of each option. The higher the ratio, the better the economic strength. If the ratio is less than 1, the measure does not pay for itself within the analysis period. The escalated savings on an annual and a special (nonannual) basis is calculated and discounted. Costs are shown on an annual and special basis for each year over the life of the system or option. Savings and investments are both discounted separately on an annual basis, and then the discounted total cumulative savings is divided by the discounted total cumulative investments (costs). The analysis period is usually the life of the system or equipment being considered.

Internal Rate of Return. The internal rate of return (IRR) method calculates a return on investment over the defined analysis period. The annual savings and costs are not discounted, and a cash flow is established for each year of the analysis period, to be used with an initial cost (or value of the loan). Annual recurring and special (nonannual) savings and costs can be used. The cash flow is then discounted until a calculated discount rate is found that yields a net present value of zero. This method assumes savings are reinvested at the same calculated rate of return; therefore, the calculated rates of return can be overstated compared to the actual rates of return.

Another version of this is the **modified** or **adjusted internal rate of return (MIRR** or **AIRR)**. In this version, reinvested savings are assumed to have a given rate of return on investment, and the financed moneys a given interest rate. The cash flow is then discounted until a calculated discount rate is found that yields a net present value of zero. This method gives a more realistic indication of expected return on investment, but the difference between alternatives can be small.

Life-Cycle Costs. This method of analysis compares the cumulative total of implementation, operating, and maintenance costs. The total costs are discounted over the life of the system or over the loan repayment period. The costs and investments are both discounted and displayed as a total combined life-cycle cost at the end of the analysis period. The options are compared to determine which has the lowest total cost over the anticipated project life.

Example 8. A municipality is evaluating two different methods of providing chilled water for cooling a government office building: purchasing chilled water from a central chilled-water utility service in the area, or installing a conventional chiller plant. Because the municipality is not a tax-paying entity, the evaluation does not need to consider taxes, allowing for either a current or constant dollar analysis.

The first-year price of the chilled-water utility service contract is $65,250 per year, and is expected to increase at a rate of 2.5% per year.

The chiller and cooling tower would cost $220,000, with an expected life of 20 years. A major overhaul ($90,000) of the chiller is expected to occur in year ten. Annual costs for preventative maintenance ($1400), labor ($10,000), water ($2000) and chemical treatments ($1800) are all expected to keep pace with inflation, which is estimated to average 3% annually over the study period. The annual electric cost

($18,750) is expected to increase at a rate of 5% per year. The municipality uses a discount rate of 8% to evaluate financial decisions.

Which option has the lowest life-cycle cost?

Solution. Table 7 compares the two alternatives. For the values provided, alternative 1 has a 20-year life cycle cost of $769,283 and alternative 2 has a 20-year life cycle cost of $717,100. If LCC is the only basis for the decision, alternative 2 is preferable because it has the lower life-cycle cost.

Computer Analysis

Many computer programs are available that incorporate economic analysis methods. These range from simple macros developed for popular spreadsheet applications to more comprehensive, menu-driven computer programs. Commonly used examples of the latter include Building Life-Cycle Cost (BLCC) and PC-ECONPACK.

BLCC was developed by the National Institute of Standards and Technology (NIST) for the U.S. Department of Energy (DOE). The program follows criteria established by the Federal Energy Management Program (FEMP) and the Office of Management and Budget (OMB). It is intended for evaluation of energy conservation investments in nonmilitary government buildings; however, it is also appropriate for similar evaluations of commercial facilities.

PC-ECONPACK, developed by the U.S. Army Corps of Engineers for use by the DOD, uses economic criteria established by the OMB. The program performs standardized life-cycle cost calculations such as net present value, equivalent uniform annual cost, SIR, and discounted payback period.

Macros developed for common spreadsheet programs generally contain preprogrammed functions for various life-cycle cost calculations. Although typically not as sophisticated as the menu-driven programs, the macros are easy to install and easy to learn.

Reference Equations

Table 8 lists commonly used discount formulas as addressed by NIST. Refer to NIST *Handbook* 135 (Fuller and Petersen 1996) for detailed discussions.

SYMBOLS

c = cooling system adjustment factor
C = total annual building HVAC maintenance cost
C_e = annual operating cost for energy
$C_{s,assess}$ = assessed system value
$C_{s,init}$ = initial system cost
$C_{s,salv}$ = system salvage value at end of study period
C_y = uniform annualized mechanical system owning, operating, and maintenance costs
CRF = capital recovery factor
CRF(i,n) = capital recovery factor for interest rate i and analysis period n
CRF(i',n) = capital recovery factory for interest rate i' for items other than fuel and analysis period n
CRF(i'',n) = capital recovery factor for fuel interest rate i'' and analysis period n
CRF(i_m,n) = capital recovery factor for loan or mortgage rate i_m and analysis period n
d = distribution system adjustment factor
D_k = depreciation during period k
$D_{k,SL}$ = depreciation during period k from straight-line depreciation method
$D_{k,SD}$ = depreciation during period k from sum-of-digits depreciation method
F = future value of sum of money
h = heating system adjustment factor
i = compound interest rate per period
i_d = discount rate per period
i_m = market mortgage rate
i' = effective interest rate for all but fuel
i'' = effective interest rate for fuel
I = insurance cost per period

Table 7   Two Alternative LCC Examples

Alternative 1: Purchase Chilled Water from Utility

					Year					
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
First costs		—	—	—	—	—	—	—	—	—	—
Chilled-water costs		$65,250	$66,881	$68,553	$70,267	$72,024	$73,824	$75,670	$77,562	$79,501	$81,488
Replacement costs		—	—	—	—	—	—	—	—	—	—
Maintenance costs		—	—	—	—	—	—	—	—	—	—
Net annual cash flow		65,250	66,881	68,553	70,267	72,024	73,824	75,670	77,501	79,501	81,488
Present value of cash flow		60,417	57,340	54,420	51,648	49,018	46,522	44,153	41,904	39,770	37,745

					Year					
	11	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Financing annual payments	—	—	—	—	—	—	—	—	—	—
Chilled-water costs	$83,526	$85,614	$87,754	$89,948	$92,197	$94,501	$96,864	$99,286	$101,768	$104,312
Replacement costs	—	—	—	—	—	—	—	—	—	—
Maintenance costs	—	—	—	—	—	—	—	—	—	—
Net annual cash flow	83,526	85,614	87,754	89,948	92,197	94,501	96,864	99,286	101,768	104,312
Present value of cash flow	35,823	33,998	32,267	30,624	29,064	27,584	26,179	24,846	23,581	22,380

20-year life-cycle cost $769,283

Alternative 2: Install Chiller and Tower

					Year					
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
First costs	$220,000	—	—	—	—	—	—	—	—	—	—
Energy costs		$18,750	$19,688	$20,672	$21,705	$22,791	$23,930	$25,127	$26,383	$27,702	$29,087
Replacement costs		—	—	—	—	—	—	—	—	—	90,000
Maintenance costs		15,200	15,656	16,126	16,609	17,108	17,621	18,150	18,694	19,255	19,833
Net annual cash flow	220,000	33,950	35,344	36,798	38,315	39,898	41,551	43,276	45,077	46,957	138,920
Present value of cash flow	220,000	31,435	30,301	29,211	28,163	27,154	26,184	25,251	24,354	23,490	64,347

					Year					
	11	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Financing annual payments	—	—	—	—	—	—	—	—	—	—
Energy costs	$30,542	$32,069	$33,672	$35,356	$37,124	$38,980	$40,929	$42,975	$45,124	$47,380
Replacement costs	—	—	—	—	—	—	—	—	—	—
Maintenance costs	20,428	21,040	21,672	22,322	22,991	23,681	24,392	25,123	25,877	26,653
Net annual cash flow	50,969	53,109	55,344	57,678	60,115	62,661	65,320	68,099	71,001	74,034
Present value of cash flow	21,860	21,090	20,350	19,637	18,951	18,290	17,654	17,042	16,452	15,884

20-year life-cycle cost $717,100

Table 8   Commonly Used Discount Formulas

Name	Algebraic Form[a,b]	Name	Algebraic Form[a,b]
Single compound-amount (SCA) equation	$F = P \cdot [(1+d)^n]$	Uniform compound account (UCA) equation	$F = A \cdot \left[\dfrac{(1+d)^n - 1}{d}\right]$
Single present value (SPW) equation	$P = F \cdot \left[\dfrac{1}{(1+d)^n}\right]$	Uniform present value (UPW) equation	$P = A \cdot \left[\dfrac{(1+d)^n - 1}{d(1+d)^n}\right]$
Uniform sinking-fund (USF) equation	$A = F \cdot \left[\dfrac{d}{(1+d)^n - 1}\right]$	Modified uniform present value (UPW*) equation	$P = A_0 \cdot \left(\dfrac{1+e}{d-e}\right) \cdot \left[1 - \left(\dfrac{1+e}{1+d}\right)^n\right]$
Uniform capital recovery (UCR) equation	$A = P \cdot \left[\dfrac{d(1+d)^n}{(1+d)^n - 1}\right]$		

where

A = end-of-period payment (or receipt) in a uniform series of payments (or receipts) over n periods at d interest or discount rate

A_0 = initial value of a periodic payment (receipt) evaluated at the beginning of the study period

$A_t = A_0 \cdot (1+e)^t$, where $t = 1,\dots, n$

d = interest or discount rate

e = price escalation rate per period

Source: NIST *Handbook* 135 (Fuller and Petersen 1996).

[a]Note that the USF, UCR, UCA, and UPW equations yield undefined answers when $d = 0$. The correct algebraic forms for this special case would be as follows: USF formula, $A = F/N$; UCR formula, $A = P/N$; UCA formula, $F = An$. The UPW* equation also yields an undefined answer when $e = d$. In this case, $P = A_0 \cdot n$.

[b]The terms by which the known values are multiplied in these equations are the formulas for the factors found in discount factor tables. Using acronyms to represent the factor formulas, the discounting equations can also be written as $F = P \times$ SCA, $P = F \times$ SPW, $A = F \times$ USF, $A = P \times$ UCR, $F = $ UCA, $P = A \times$ UPW, and $P = A_0 \times$ UPW*.

ITC = investment tax credit

j = inflation rate per period

j_e = fuel inflation rate per period

k = end of period(s) during which replacement(s), repair(s), depreciation, or interest are calculated

M = maintenance cost per period

n = number of periods under analysis

P = present value of a sum of money

P_k = outstanding principle on loan at end of period k

PMT = future equal payments

PWF = present worth factor

$PWF(i_d,k)$ = present worth factor for discount rate i_d at end of period k

$PWF(i',k)$ = present worth factor for effective interest rate i' at end of period k

$PWF(i,n)_{sgl}$ = single payment present worth factor

$PWF(i,n)_{ser}$ = present worth factor for a series of future equal payments

R_k = net replacement, repair, or disposal costs at end of period k

T_{inc} = net income tax rate

T_{prop} = property tax rate

T_{salv} = tax rate applicable to salvage value of system

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CHAPTER 37

TESTING, ADJUSTING, AND BALANCING

SYSTEMS that control the environment in a building change with time and use, and must be rebalanced accordingly. The designer must consider initial and supplementary testing and balancing requirements for commissioning. Complete and accurate operating and maintenance instructions that include intent of design and how to test, adjust, and balance the building systems are essential. Building operating personnel must be well-trained, or qualified operating service organizations must be employed to ensure optimum comfort, proper process operations, and economical operation.

This chapter does not suggest which groups or individuals should perform a complete testing, adjusting, and balancing procedure. However, the procedure must produce repeatable results that meet the design intent and the owner's requirements. Overall, one source must be responsible for testing, adjusting, and balancing all systems. As part of this responsibility, the testing organization should check all equipment under field conditions to ensure compliance.

Testing and balancing should be repeated as systems are renovated and changed. Testing boilers and other pressure vessels for compliance with safety codes is not the primary function of the testing and balancing firm; rather, it is to verify and adjust operating conditions in relation to design conditions for flow, temperature, pressure drop, noise, and vibration. ASHRAE *Standard* 111 details procedures not covered in this chapter.

TERMINOLOGY

Testing, adjusting, and balancing (TAB) is the process of checking and adjusting all environmental systems in a building to produce the design objectives. This process includes (1) balancing air and water distribution systems, (2) adjusting the total system to provide design quantities, (3) electrical measurement, (4) establishing quantitative performance of all equipment, (5) verifying automatic control system operation and sequences of operation, and (6) sound and vibration measurement. These procedures are accomplished by checking installations for conformity to design, measuring and establishing the fluid quantities of the system as required to meet design specifications, and recording and reporting the results.

The following definitions are used in this chapter. Refer to ASHRAE *Terminology of HVAC&R* (1991) for additional definitions.

Test. Determine quantitative performance of equipment.

Adjust. Regulate the specified fluid flow rate and air patterns at terminal equipment (e.g., reduce fan speed, adjust a damper).

Balance. Proportion flows in the distribution system (submains, branches, and terminals) according to specified design quantities.

Balanced System. A system designed to deliver heat transfer required for occupant comfort or process load at design conditions. A minimum heat transfer of 97% should be provided to the space or

load served at design flow. The flow required for minimum heat transfer establishes the system's flow tolerance. The fluid distribution system should be designed to allow flow to maintain the required tolerance and verify its performance.

Procedure. An approach to and execution of a sequence of work operations to yield repeatable results.

Report forms. Test data sheets arranged in logical order for submission and review. They should also form the permanent record to be used as the basis for any future TAB work.

Terminal. A point where the controlled medium (fluid or energy) enters or leaves the distribution system. In air systems, these may be variable- or constant-volume boxes, registers, grilles, diffusers, louvers, and hoods. In water systems, these may be heat transfer coils, fan-coil units, convectors, or finned-tube radiation or radiant panels.

GENERAL CRITERIA

Effective and efficient TAB requires a systematic, thoroughly planned procedure implemented by experienced and qualified staff. All activities, including organization, calibration of instruments, and execution of the work, should be scheduled. Air-side work must be coordinated with water-side and control work. Preparation includes planning and scheduling all procedures, collecting necessary data (including all change orders), reviewing data, studying the system to be worked on, preparing forms, and making preliminary field inspections.

Air leakage in a conduit (duct) system can significantly reduce performance, so conduits (ducts) must be designed, constructed, and installed to minimize and control leakage. During construction, all duct systems should be sealed and tested for air leakage. Water, steam, and pneumatic piping should be tested for leakage, which can harm people and equipment.

Design Considerations

TAB begins as design functions, with most of the devices required for adjustments being integral parts of the design and installation. To ensure that proper balance can be achieved, the engineer should show and specify a sufficient number of dampers, valves, flow measuring locations, and flow-balancing devices; these must be properly located in required straight lengths of pipe or duct for accurate measurement. Testing depends on system characteristics and layout. Interaction between individual terminals varies with pressures, flow requirements, and control devices.

The design engineer should specify balancing tolerances. Minimum flow tolerances are ±10% for individual terminals and branches in noncritical applications and ±5% for main air ducts. For critical water systems where differential pressures must be maintained, tolerances of ±5% are suggested. For critical air systems, recommendations are the following:

The preparation of this chapter is assigned to TC 7.7, Testing and Balancing.

Positive zones:
    Supply air   0 to +10%
    Exhaust and return air   0 to −10%
Negative zones:
    Supply air   0 to −10%
    Exhaust and return air   0 to +10%

Balancing Devices. Balancing devices should be used to provide maximum flow-limiting ability without causing excessive noise. Flow reduction should be uniform over the entire duct or pipe. Single-blade dampers or butterfly balancing valves are not good balancing valves because of the uneven flow pattern at high pressure drops. Pressure drop across equipment is not an accurate flow measurement but can be used to determine whether the manufacturer design pressure is within specified limits. Liberal use of pressure taps at critical points is recommended.

AIR VOLUMETRIC MEASUREMENT METHODS

General

The pitot-tube traverse is the generally accepted method of measuring airflow in ducts; ways to measure airflow at individual terminals are described by manufacturers. The primary objective is to establish repeatable measurement procedures that correlate with the pitot-tube traverse.

Laboratory tests, data, and techniques prescribed by equipment and air terminal manufacturers must be reviewed and checked for accuracy, applicability, and repeatability of results. Conversion factors that correlate field data with laboratory results must be developed to predict the equipment's actual field performance.

Air Devices

All flow-measuring instruments should be field verified by comparing to pitot-tube traverses to establish correction and/or density factors.

Generally, correction factors given by air diffuser manufacturers should be checked for accuracy by field measurement and by comparing actual flow measured by pitot-tube traverse to actual measured velocity. Air diffuser manufacturers usually base their volumetric test measurements on a deflecting vane anemometer. The velocity is multiplied by an empirical effective area to obtain the air diffuser's delivery. Accurate results are obtained by measuring at the vena contracta with the probe of the deflecting vane anemometer. Methods advocated for measuring airflow of troffer-type terminals are similar to those for air diffusers.

A capture hood is frequently used to measure device airflows, primarily of diffusers and slots. Loss coefficients should be established for hood measurements with varying flow and deflection settings. If the air does not fill the measurement grid, the readings will require a correction factor.

Rotating vane anemometers are commonly used to measure airflow from sidewall grilles. Effective areas (correction factors) should be established with the face dampers fully open and deflection set uniformly on all grilles. Correction factors are required when measuring airflow in open ducts [i.e., damper openings and fume hoods (Sauer and Howell 1990)].

Duct Flow

The preferred method of measuring duct volumetric flow is the pitot-tube traverse average. The maximum straight run should be obtained before and after the traverse station. To obtain the best duct velocity profile, measuring points should be located as shown in Chapter 14 of the 2005 *ASHRAE Handbook—Fundamentals* and ASHRAE *Standard* 111. When using factory-fabricated volume-measuring stations, the measurements should be checked against a pitot-tube traverse.

Power input to a fan's driver should be used as only a guide to indicate its delivery; it may also be used to verify performance determined by a reliable method (e.g., pitot-tube traverse of system's main) that considers possible system effects. For some fans, the flow rate is not proportional to the power needed to drive them. In some cases, as with forward-curved-blade fans, the same power is required for two or more flow rates. The backward-curved-blade centrifugal fan is the only type with a flow rate that varies directly with power input.

If an installation has an inadequate straight length of ductwork or no ductwork to allow a pitot-tube traverse, the procedure from Sauer and Howell (1990) can be followed: a vane anemometer reads air velocities at multiple points across the face of a coil to determine a loss coefficient.

Mixture Plenums

Approach conditions are often so unfavorable that the air quantities comprising a mixture (e.g., outside and return air) cannot be determined accurately by volumetric measurements. In such cases, the mixture's temperature indicates the balance (proportions) between the component airstreams. Temperatures must be measured carefully to account for stratification, and the difference between outside and return temperatures must be greater than 20°F. The temperature of the mixture can be calculated as follows:

$$Q_t t_m = Q_o t_o + Q_r t_r \tag{1}$$

where

    Q_t = total measured air quantity, %
    Q_o = outside air quantity, %
    Q_r = return air quantity, %
    t_m = temperature of outside and return mixture, °F
    t_o = outside temperature, °F
    t_r = return temperature, °F

Pressure Measurement

Air pressures measured include barometric, static, velocity, total, and differential. For field evaluation of air-handling performance, pressure should be measured per ASHRAE *Standard* 111 and analyzed together with manufacturers' fan curves and system effect as predicted by AMCA *Standard* 210. When measured in the field, pressure readings, air quantity, and power input often do not correlate with manufacturers' certified performance curves unless proper correction is made.

Pressure drops through equipment such as coils, dampers, or filters should not be used to measure airflow. Pressure is an acceptable means of establishing flow volumes only where it is required by, and performed in accordance with, the manufacturer certifying the equipment.

Stratification

Normal design minimizes conditions causing air turbulence, to produce the least friction, resistance, and consequent pressure loss. Under some conditions, however, air turbulence is desirable and necessary. For example, two airstreams of different temperatures can stratify in smooth, uninterrupted flow conditions. In this situation, design should promote mixing. Return and outside airstreams at the inlet side of the air-handling unit tend to stratify where enlargement of the inlet plenum or casing size decreases air velocity. Without a deliberate effort to mix the two airstreams (e.g., in cold climates, placing the outside air entry at the top of the plenum and return air at the bottom of the plenum to allow natural mixing), stratification can be carried throughout the system (e.g., filter, coils, eliminators, fans, ducts). Stratification can freeze coils and rupture tubes, and can affect temperature control in plenums, spaces, or both.

Stratification can also be reduced by adding vanes to break up and mix the airstreams. No solution to stratification problems is guaranteed; each condition must be evaluated by field measurements and experimentation.

BALANCING PROCEDURES FOR
AIR DISTRIBUTION

No one established procedure is applicable to all systems. The bibliography lists sources of additional information.

Instruments for Testing and Balancing

The minimum instruments necessary for air balance are

- Manometer calibrated in 0.005 in. of water divisions
- Combination inclined/vertical manometer (0 to 10 in. of water)
- Pitot tubes in various lengths, as required
- Tachometer (direct-contact, self-timing) or strobe light
- Clamp-on ammeter with voltage scales [root-mean-square (RMS) type]
- Rotating vane anemometer
- Deflecting vane anemometer
- Thermal anemometer
- Capture hood
- Digital thermometers (0.1°F increments as a minimum) and glass stem thermometers (0.1°F graduations minimum)
- Sound level meter with octave band filter set, calibrator, and microphone
- Vibration analyzer capable of measuring displacement velocity and acceleration
- Water flowmeters (0 to 50 in. of water and 0 to 400 in. of water ranges)
- Compound gage
- Test gages (100 psi and 300 psi)
- Sling psychrometer
- Etched-stem thermometer (30 to 120°F in 0.1°F increments)
- Hygrometers
- Relative humidity and dew-point instruments

Instruments must be calibrated periodically to verify their accuracy and repeatability before use in the field.

Preliminary Procedure for Air Balancing

1. Before balancing, all pressure tests (duct leakage) of duct and piping systems must be complete and acceptable.
2. Obtain as-built design drawings and specifications, and become thoroughly acquainted with the design intent.
3. Obtain copies of approved shop drawings of all air-handling equipment, outlets (supply, return, and exhaust), and temperature control diagrams, including performance curves. Compare design requirements with shop drawing capacities.
4. Compare design to installed equipment and field installation.
5. Walk the system from air-handling equipment to terminal units to determine variations of installation from design.
6. Check dampers (both volume and fire) for correct and locked position and temperature control for completeness of installation before starting fans.
7. Prepare report test sheets for both fans and outlets. Obtain manufacturer's outlet factors and recommended test procedure. A summation of required outlet volumes allows cross-checking with required fan volumes.
8. Determine the best locations in the main and branch ductwork for the most accurate duct traverses.
9. Place all outlet dampers in full open position.
10. Prepare schematic diagrams of system as-built ductwork and piping layouts to facilitate reporting.
11. Check filters for cleanliness and proper installation (no air bypass). If specifications require, establish procedure to simulate dirty filters.
12. For variable-volume systems, develop a plan to simulate diversity (if required).

Equipment and System Check

1. All fans (supply, return, and exhaust) must be operating before checking the following items:

   - Motor amperage and voltage to guard against overload
   - Fan rotation
   - Operability of static pressure limit switch
   - Automatic dampers for proper position
   - Air and water controls operating to deliver required temperatures
   - Air leaks in the casing and around the coils and filter frames must be stopped. Note points where piping enters the casing to ensure that escutcheons are right. Do not rely on pipe insulation to seal these openings (insulation may shrink). In prefabricated units, check that all panel-fastening holes are filled.

2. Traverse the main supply ductwork whenever possible. All main branches should also be traversed where duct arrangement allows. Traverse points and method of traverse should be selected as follows:

   - Traverse each main or branch after the longest possible straight run for the duct involved.
   - For test hole spacing, refer to Chapter 14 of the 2005 *ASHRAE Handbook—Fundamentals*.
   - Traverse using a pitot tube and manometer where velocities are over 600 fpm. Below this velocity, use either a micromanometer and pitot tube or an electronic multimeter and a pitot tube.
   - Note temperature and barometric pressure and correct for standard air quantity if needed.
   - After establishing the total air being delivered, adjust fan speed to obtain design airflow, if necessary. Check power and speed to confirm motor power and/or critical fan speed are not exceeded.
   - Proportionally adjust branch dampers until each has the proper air volume.
   - With all dampers and registers in the system proportioned and with supply and return fans operating at or near design airflow, set the minimum outside and return air ratio. If duct traverse locations are not available, this can be done by measuring the mixture temperature in the return air, outside air louver, and filter section. The mixture temperature may be approximated from Equation (1).

     The greater the temperature difference between outside and return air, the easier it is to get accurate damper settings. Take the temperature at many points in a uniform traverse to be sure there is no stratification.

     After the minimum outside air damper has been set for the proper percentage of outside air, run another traverse of mixture temperatures and install baffling if variation from the average is more than 5%. Remember that stratified mixed-air temperatures vary greatly with outside temperature in cold weather, whereas return air temperature has only a minor effect.

3. Balance terminal outlets in each control zone in proportion to each other, as follows:

   - Once the preliminary fan quantity is set, proportion the terminal outlet balance from the outlets into the branches to the fan. Concentrate on proportioning the flow rather than the absolute quantity. As fan settings and branch dampers change, the outlet terminal quantities remain proportional. Branch dampers should be used for major adjusting and terminal dampers for trim or minor adjustment only. It may be necessary to install additional sub-branch dampers to decrease the use of terminal dampers that create objectionable noise.
   - Normally, several passes through the entire system are necessary to obtain proper outlet values.
   - The total tested outlet air quantity compared to duct traverse air quantities may indicate duct leakage.
   - With total design air established in the branches and at the outlets, (1) take new fan motor amperage readings, (2) find static pressure across the fan, (3) read and record static pressure

across each component (intake, filters, coils, mixing dampers), and (4) take a final duct traverse.

Multizone Systems

Balancing should be accomplished as follows:

1. When adjusting multizone constant-volume systems, establish the ratio of the design volume through the cooling coil to total fan volume to achieve the desired diversity factor. Keep the proportion of cold to total air constant during the balance. However, check each zone on full cooling. If the design calls for full flow through the cooling coil, the entire system should be set to full flow through the cooling side while making tests. Perform the same procedure for the hot-air side.
2. Check leaving air temperature at each zone to verify that hot and cold damper inlet leakage is not greater than the established maximum allowable leakage.
3. Check apparatus and main trunks, as outlined in the section on Equipment and System Check.
4. Proportionately balance diffusers or grilles.
5. Change control settings to full heating, and ensure that controls function properly. Verify airflow at each diffuser. Check for stratification.
6. If the engineer included a diversity factor in selecting the main apparatus, it will not be possible to get full flow to all zones simultaneously, as outlined in item 3 under Equipment and System Check. Zones equaling the diversity should be set to heating.

Dual-Duct Systems

Balancing should be accomplished as follows:

1. When adjusting dual-duct constant-volume systems, establish the ratio of the design volume through the cooling coil to total fan volume to achieve the desired diversity factor. Keep the proportion of cold to total air constant during the balance. If the design calls for full flow through the cooling coil, the entire system should be set to full flow through the cooling side while making tests. Perform the same procedure for the hot-air side.
2. Check leaving air temperature at the nearest terminal to verify that hot and cold damper inlet leakage is not greater than the established maximum allowable leakage.
3. Check apparatus and main trunks, as outlined in the section on Equipment and System Check.
4. Determine whether static pressure at the end of the system (the longest duct run) is at or above the minimum required for mixing box operation. Proceed to extreme end of the system and check the static pressure with an inclined manometer. Pressure should exceed the minimum static pressure recommended by the mixing box manufacturer.
5. Proportionately balance diffusers or grilles on the low-pressure side of the box, as described for low-pressure systems in the previous section.
6. Change control settings to full heating, and ensure that the controls and dual-duct boxes function properly. Spot-check airflow at several diffusers. Check for stratification.
7. If the engineer has included a diversity factor in selecting the main apparatus, it will not be possible to get full flow from all boxes simultaneously, as outlined in item 3 under Equipment and System Check. Mixing boxes closest to the fan should be set to full heating to force the air to the end of the system.

VARIABLE-VOLUME SYSTEMS

Many types of variable-air-volume (VAV) systems have been developed to conserve energy. They can be categorized as pressure-dependent or pressure-independent.

Pressure-dependent systems incorporate air terminal boxes with a thermostat signal controlling a damper actuator. Air volume to the space varies to maintain space temperature; air temperature supplied

to terminal boxes remains constant. The balance of this system constantly varies with loading changes; therefore, any balancing procedure will not produce repeatable data unless changes in system load are simulated by using the same configuration of thermostat settings each time the system is tested (i.e., the same terminal boxes are fixed in the minimum and maximum positions for the test). Each terminal box requires a balancing damper upstream of its inlet.

In a pressure-dependent system with pneumatic controls, setting minimum airflows to the space (other than at no flow) is not suggested unless the terminal box has a normally closed damper and the manufacturer of the damper actuator provides adjustable mechanical stops.

Pressure-independent systems incorporate air terminal boxes with a thermostat signal used as a master control to open or close the damper actuator, and a velocity controller used as a sub-master control to maintain the maximum and minimum amounts of air to be supplied to the space. Air volume to the space varies to maintain the space temperature; air temperature supplied to the terminal remains constant. Take care to verify the operating range of the damper actuator as it responds to the velocity controller to prevent dead bands or overlap of control in response to other system components (e.g., double-duct VAV, fan-powered boxes, retrofit systems). Care should also be taken to verify the action of the thermostat with regard to the damper position, as the velocity controller can change the control signal ratio or reverse the control signal.

The pressure-independent system requires verifying that the velocity controller is operating properly; it can be adversely affected by inlet duct configurations if a multipoint sensor is not used (Griggs et al. 1990). The primary difference between the two systems is that the pressure-dependent system supplies a different amount of air to the space as pressure upstream of the terminal box changes. If the thermostats are not calibrated properly to meet the space load, zones may overcool or overheat. When zones overcool and receive greater amounts of supply air than required, they decrease the amount of air that can be supplied to overheated zones. The pressure-independent system is not affected by improper thermostat calibration in the same way as a pressure-dependent system, because minimum and maximum airflow limits may be set for each zone.

Static Control

Static control saves energy and prevents overpressurizing the duct system. The following procedures and equipment are some of the means used to control static pressure.

Fan Control. Consult ASHRAE *Standard* 90.1.

Discharge Damper. Losses and noise should be considered.

Vortex Damper. Losses from inlet air conditions are a problem, and the vortex damper does not completely close. The minimum expected airflow should be evaluated.

Variable Inlet Cones. System loss can be a problem because the cone does not typically close completely. The minimum expected airflow should be evaluated.

Varying Fan Speed Mechanically. Slippage, loss of belts, cost of belt replacement, and the initial cost of components are concerns.

Variable Pitch-in-Motion Fans. Maintenance and preventing the fan from running in the stall condition must be evaluated.

Varying Fan Speed Electrically. Varying voltage or frequency to the fan motor is usually the most efficient method. Some motor drives may cause electrical noise and affect other devices.

In controlling VAV fan systems, location of the static pressure sensors is critical and should be field-verified to give the most representative point of operation. After the terminal boxes have been proportioned, static pressure control can be verified by observing static pressure changes at the fan discharge and the static pressure sensor as load is simulated from maximum to minimum airflow (i.e., set all terminal boxes to balanced airflow conditions and determine whether any changes in static pressure occur by placing one terminal box at a time to minimum airflow, until all terminals are

placed at the minimal airflow setting). The maximum to minimum air volume changes should be within the fan curve performance (speed or total pressure).

Diversity

Diversity may be used on a VAV system, assuming that total airflow is lower by design and that all terminal boxes never fully open at the same time. Duct leakage should be avoided. All ductwork upstream of the terminal box should be considered medium-pressure, whether in a low- or medium-pressure system.

A procedure to test the total air on the system should be established by setting terminal boxes to the zero or minimum position nearest the fan. During peak load conditions, care should be taken to verify that adequate pressure is available upstream of all terminal boxes to achieve design airflow to the spaces.

Outside Air Requirements

Maintaining a space under a slight positive or neutral pressure to atmosphere is difficult with all variable-volume systems. In most systems, the exhaust requirement for the space is constant; thus, outside air used to equal the exhaust air and meet minimum outside air requirements for building codes must also remain constant. Because of the location of the outside air intake and pressure changes, this does not usually happen. Outside air should enter the fan at a point of constant pressure (i.e., supply fan volume can be controlled by proportional static pressure control, which can control the return air fan volume). Makeup air fans can also be used for outside air control.

Return Air Fans

If return air fans are required in series with a supply fan, control and sizing of the fans is most important. Serious over- and under-pressurization can occur, especially during economizer cycles.

Types of VAV Systems

Single-Duct VAV. This system uses a pressure-dependent or -independent terminal and usually has reheat at a minimal setting on the terminal unit, or a separate heating system. Consult ASHRAE *Standard* 90.1 when considering this system.

Bypass. This system uses a pressure-dependent damper, which, on demand for heating, closes the damper to the space and opens to the return air plenum. Bypass sometimes uses a constant bypass airflow or a reduced amount of airflow bypassed to the return air plenum in relation to the amount supplied to the space. No economic value can be obtained by varying fan speed with this system. A control problem can exist if any return air sensing is done to control a warmup or cool-down cycle. Consult ASHRAE *Standard* 90.1 when considering this system.

VAV Using Single-Duct VAV and Fan-Powered, Pressure-Dependent Terminals. This system has a primary source of air from the fan to the terminal and a secondary powered fan source that pulls air from the return air plenum before the additional heat source. In some fan-powered boxes, backdraft dampers allow duct leakage when the system calls for the damper to be fully closed. Typical applications include geographic areas where the ratio of heating hours to cooling hours is low.

Double-Duct VAV. This type of terminal uses two single-duct variable terminals. It is controlled by velocity controllers that operate in sequence so that both hot and cold ducts can be opened or closed. Some controls have a downstream flow sensor in the terminal unit. The total-airflow sensor is in the inlet and controlled by the thermostat. As this inlet damper closes, the downstream controller opens the other damper to maintain set airflow. Low pressure in the decks controlled by the thermostat may cause unwanted mixing of air, which results in excess energy use or discomfort in the space.

Balancing the VAV System

The general procedure for balancing a VAV system is

1. Determine the required maximum air volume to be delivered by the supply and return air fans. Load diversity usually means that the volume will be somewhat less than the outlet total.
2. Obtain fan curves on these units, and request information on surge characteristics from the fan manufacturer.
3. If inlet vortex damper control is used, obtain the fan manufacturer's data on deaeration of the fan when used with the damper. If speed control is used, find the maximum and minimum speed that can be used on the project.
4. Obtain from the manufacturer the minimum and maximum operating pressures for terminal or variable-volume boxes to be used on the project.
5. Construct a theoretical system curve, including an approximate surge area. The system curve starts at the boxes' minimum inlet static pressure, plus system loss at minimum flow, and terminates at the design maximum flow. The operating range using an inlet vane damper is between the surge line intersection with the system curve and the maximum design flow. When variable-speed control is used, the operating range is between (1) the minimum speed that can produce the necessary minimum box static pressure at minimum flow still in the fan's stable range and (2) the maximum speed necessary to obtain maximum design flow.
6. Position the terminal boxes to the proportion of maximum fan air volume to total installed terminal maximum volume.
7. Proportion outlets, and verify design volume with the VAV box on maximum flow. Verify minimum flow setting.
8. Set the fan to operate at approximate design speed.
9. Verify flow at all terminal boxes. Identify which boxes are not in control and the inlet static pressures, if any. If all terminal boxes are in control, reduce the fan flow until the remote terminals are just in control and within the tolerances of filter loading.
10. Run a total air traverse with a pitot tube.
11. Run steps (8) through (10) with the return or exhaust fan set at design flow as measured by a pitot-tube traverse and with the system set on minimum outside air.
12. Set terminals to minimum, and adjust the inlet vane or speed controller until minimum static pressure and airflow are obtained.
13. Temperature control personnel, balancing personnel, and the design engineer should agree on final placement of the sensor for the static pressure controller. This sensor must be placed in a representative location in the supply duct to sense average maximum and minimum static pressures in the system.
14. Check return air fan speed or its inlet vane damper, which tracks or adjusts to the supply fan airflow, to ensure proper outside air volume.
15. Operate the system on 100% outside air (weather permitting), and check supply and return fans for proper power and static pressure.

Induction Systems

Most induction systems use high-velocity air distribution. Balancing should be accomplished as follows:

1. For apparatus and main trunk capacities, perform general VAV balancing procedures.
2. Determine primary airflow at each terminal unit by reading the unit plenum pressure with a manometer and locating the point on the charts (or curves) of air quantity versus static pressure supplied by the unit manufacturer.
3. Normally, about three complete passes around the entire system are required for proper adjustment. Make a final pass without adjustments to record the end result.

4. To provide the quietest possible operation, adjust the fan to run at the slowest speed that provides sufficient nozzle pressure to all units with minimum throttling of all unit and riser dampers.
5. After balancing each induction system with minimum outside air, reposition to allow maximum outside air and check power and static pressure readings.

Report Information

To be of value to the consulting engineer and owner's maintenance department, the air-handling report should consist of at least the following items:

1. *Design*
   • Air quantity to be delivered
   • Fan static pressure
   • Motor power installed or required
   • Percent of outside air under minimum conditions
   • Fan speed
   • Input power required to obtain this air quantity at design static pressure

2. *Installation*
   • Equipment manufacturer (indicate model and serial numbers)
   • Size of unit installed
   • Arrangement of air-handling unit
   • Nameplate power and voltage, phase, cycles, and full-load amperes of installed motor

3. *Field tests*
   • Fan speed
   • Power readings (voltage, amperes of all phases at motor terminals)
   • Total pressure differential across unit components
   • Fan suction and fan discharge static pressure (equals fan total pressure)
   • Plot of actual readings on manufacturer's fan performance curve to show the installed fan operating point
   • Measured airflow rate

   It is important to establish initial static pressures accurately for the air treatment equipment and duct system so that the variation in air quantity caused by filter loading can be calculated. It enables the designer to ensure that the total air quantity never is less than the minimum requirements. Because the design air quantity for peak loading of the filters has already been calculated, it also serves as a check of dirt loading in coils.

4. *Terminal Outlets*
   • Outlet by room designation and position
   • Manufacture and type
   • Size (using manufacturer's designation to ensure proper factor)
   • Manufacturer's outlet factor [where no factors are available, or field tests indicate listed factors are incorrect, a factor must be determined in the field by traverse of a duct leading to a single outlet); this also applies to capture hood readouts (see ASHRAE *Standard* 111)]
   • Adjustment pattern for every air terminal

5. *Additional Information (if applicable)*
   • Air-handling units
     - Belt number and size
     - Drive and driven sheave size
     - Belt position on adjusted drive sheaves (bottom, middle, and top)
     - Motor speed under full load
     - Motor heater size
     - Filter type and static pressure at initial use and full load; time to replace
     - Variations of velocity at various points across face of coil
     - Existence of vortex or discharge dampers, or both

• Distribution system
  - Unusual duct arrangements
  - Branch duct static readings in double-duct and induction system
  - Ceiling pressure readings where plenum ceiling distribution is used; tightness of ceiling
  - With wind conditions outside less than 5 mph, relationship of building to outside pressure under both minimum and maximum outside air
  - Induction unit manufacturer and size (including required air quantity and plenum pressures for each unit) and test plenum pressure and resulting primary air delivery from manufacturer's listed curves
• All equipment nameplates visible and easily readable

Many independent firms have developed detailed procedures suitable to their own operations and the area in which they function. These procedures are often available for information and evaluation on request.

PRINCIPLES AND PROCEDURES FOR BALANCING HYDRONIC SYSTEMS

Heat Transfer at Reduced Flow Rate

The typical heating-only hydronic terminal (200°F, 20°F Δt) gradually reduces heat output as flow is reduced (Figure 1). Decreasing water flow to 20% of design reduces heat transfer to 65% of that at full design flow. The control valve must reduce water flow to 10% to reduce heat output to 50%. This relative insensitivity to changing flow rates is because the governing coefficient for heat transfer is the air-side coefficient; a change in internal or water-side coefficient with flow rate does not materially affect the overall heat transfer coefficient. This means (1) heat transfer for water-to-air terminals is established by the mean air-to-water temperature difference, (2) heat transfer is measurably changed, and (3) a change in mean water temperature requires a greater change in water flow rate.

Tests of hydronic coil performance show that when flow is throttled to the coil, the water-side differential temperature of the coil increases with respect to design selection. This applies to both constant-volume and variable-volume air-handling units. In
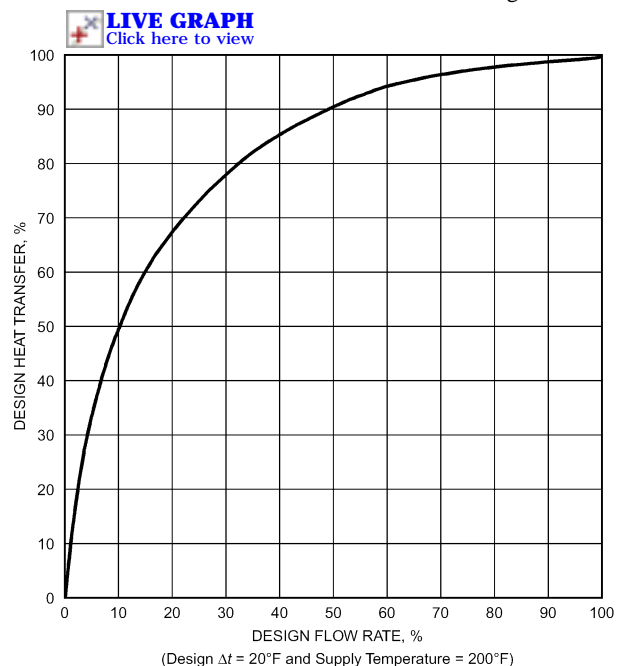
Fig. 1   Effects of Flow Variation on Heat Transfer from a Hydronic Terminal
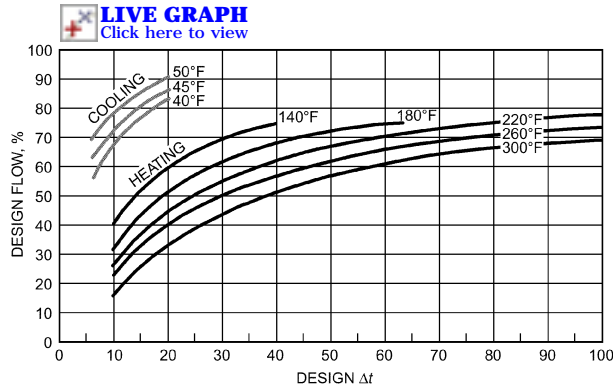
Fig. 2 Percent of Design Flow Versus Design Δt to Maintain 90% Terminal Heat Transfer for Various Supply Water Temperatures

constantly circulated coils that control temperature by changing coil entering water temperature, decreasing source flow to the circuit decreases the water-side differential temperature.

A secondary concern applies to heating terminals. Unlike chilled water, hot water can be supplied at a wide range of temperatures. Inadequate terminal heating capacity caused by insufficient flow can sometimes be overcome by raising supply water temperature. Design below the 250°F limit (ASME low-pressure boiler code) must be considered.

Figure 2 shows the flow variation when 90% terminal capacity is acceptable. Note that heating tolerance decreases with temperature and flow rates and that chilled-water terminals are much less tolerant of flow variation than hot-water terminals.

Dual-temperature heating/cooling hydronic systems are sometimes first started during the heating season. Adequate heating ability in the terminals may suggest that the system is balanced. Figure 2 shows that 40% of design flow through the terminal provides 90% of design heating with 140°F supply water and a 10°F temperature drop. Increased supply water temperature establishes the same heat transfer at terminal flow rates of less than 40% design.

Sometimes, dual-temperature water systems have decreased flow during the cooling season because of chiller pressure drop; this could cause a flow reduction of 25%. For example, during the cooling season, a terminal that heated satisfactorily would only receive 30% of the design flow rate.

Although the example of reduced flow rate at Δt = 20°F only affects heat transfer by 10%, this reduced heat transfer rate may have the following negative effects:

• Object of the system is to deliver (or remove) heat where required. When flow is reduced from design rate, the system must supply heating or cooling for a longer period to maintain room temperature.
• As load reaches design conditions, the reduced flow rate is unable to maintain room design conditions.
• Control valves with average range ability (30:1) and reasonable authority (β = 0.5) may act as on/off controllers instead of throttling flows to the terminal. The resultant change in riser friction loss may cause overflow or underflow in other system terminals. Attempting to throttle may cause wear on the valve plug or seat because of higher velocities at the vena contracta of the valve. In extreme situations, cavitations may occur.

Terminals with lower water temperature drops have greater tolerance for unbalanced conditions. However, larger water flows are necessary, requiring larger pipes, pumps, and pumping cost.

System balance becomes more important in terminals with a large temperature difference. Less water flow is required, which reduces the size of pipes, valves, and pumps, as well as pumping costs. A more linear emission curve gives better system control. If flow
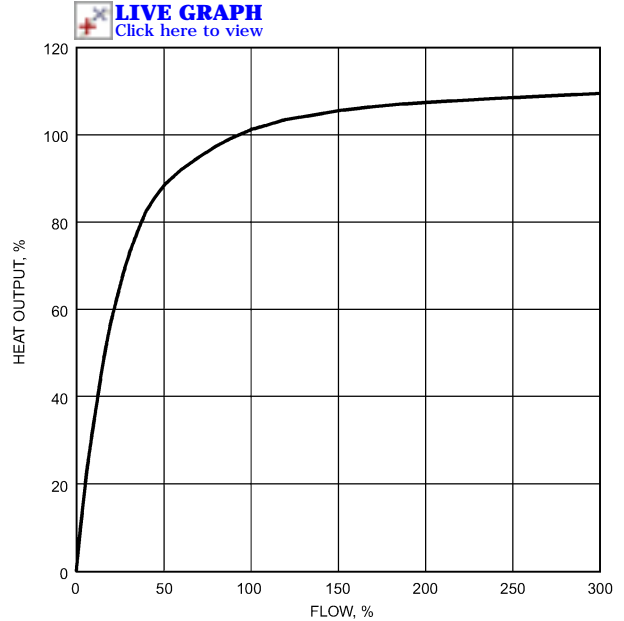
Fig. 3 Typical Heating Coil Heat Transfer Versus Water Flow

Table 1 Load Flow Variation

| Load Type | % Design Flow at 90% Load | Other Load, Order of % | | |
		Sensible	Total	Latent
Sensible	65	90	84	58
Total	75	95	90	65
Latent	90	98	95	90

Note: Dual-temperature systems are designed to chilled flow requirements and often operate on a 10°F temperature drop at full-load heating.

varies by more than 5% at design flow conditions, heat transfer can fall off rapidly, ultimately causing poorer control of the wet-bulb temperature and potentially decreasing system air quality.

Heat Transfer at Excessive Flow

Increasing the flow rate above design in an effort to increase heat transfer requires careful consideration. Figure 3 shows that increasing the flow to 200% of design only increases heat transfer by 6% but increases resistance or pressure drop four times and power by the cube of the original power (pump laws) for a lower design Δt. In coils with larger water-side design Δt, heat transfer can increase.

Generalized Chilled Water Terminal—Heat Transfer Versus Flow

Heat transfer for a typical chilled-water coil in an air duct versus water flow rate is shown in Figure 4. The curves are based on ARI rating points: 45°F inlet water at a 10°F rise with entering air at 80°F db and 67°F wb. The basic curve applies to catalog ratings for lower dry-bulb temperatures providing a consistent entering-air moisture content (e.g., 75°F db, 65°F wb). Changes in inlet water temperature, temperature rise, air velocity, and dry- and wet-bulb temperatures cause terminal performance to deviate from the curves. Figure 4 is only a general representation and does not apply to all chilled-water terminals. Comparing Figure 4 with Figure 1 indicates the similarity of nonlinear heat transfer and flow for both the heating and cooling terminals.

Table 1 shows that if the coil is selected for the load and flow is reduced to 90% of load, three flow variations can satisfy the reduced load at various sensible and latent combinations. Note that the reduction in flow will not maintain a chilled-water design differential when coil velocity drops below 1.5 fps. This affects chiller loading and unloading.
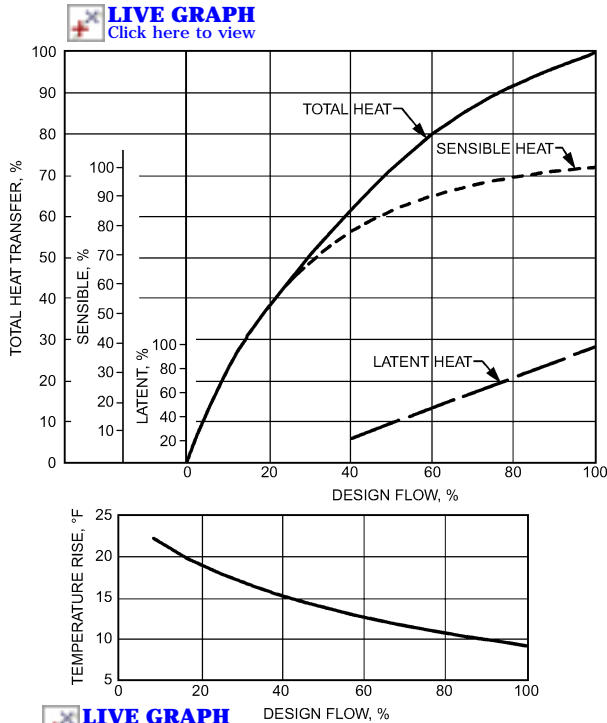
Fig. 4   Chilled Water Terminal Heat Transfer Versus Flow

Flow Tolerance and Balance Procedure

The design procedure rests on a design flow rate and an allowable flow tolerance. The designer must define both the terminal's flow rates and feasible flow tolerance, remembering that the cost of balancing rises with tightened flow tolerance. Any overflow increases pumping cost, and any flow decrease reduces the maximum heating or cooling at design conditions.

WATER-SIDE BALANCING

Water-side balancing adjustments should be made with a thorough understanding of piping friction loss calculations and measured system pressure losses. It is good practice to show expected losses of pipes, fittings, and terminals and expected pressures in operation on schematic system drawings.

The water side should tested by direct flow measurement. This method is accurate because it deals with system flow as a function of differential pressures, and avoids compounding errors introduced by temperature difference procedures. Measuring flow at each terminal enables proportional balancing and, ultimately, matching pump head and flow to actual system requirements by trimming the pump impeller or reducing pump motor power. Often, reducing pump operating cost pays for the cost of water-side balancing.

Equipment

Proper equipment selection and preplanning are needed to successfully balance hydronic systems. Circumstances sometimes dictate that flow, temperature, and pressure be measured. The designer should specify the water flow balancing devices for installation during construction and testing during hydronic system balancing. The devices may consist of all or some of the following:

- Flowmeters (ultrasonic stations, turbines, venturi, orifice plate, multiported pitot tubes, and flow indicators)
- Manometers, ultrasonic digital meters, and differential pressure gages (analog or digital)
- Portable digital meter to measure flow and pressure drop
- Portable pyrometers to measure temperature differentials when test wells are not provided

- Test pressure taps, pressure gages, thermometers, and wells.
- Balancing valve with a factory-rated flow coefficient C_v, a flow versus handle position and pressure drop table, or a slide rule flow calculator
- Dynamic balancing valves or flow-limiting valves (for prebalanced systems only); field adjustment of these devices is not normally required or possible (see Chapter 46)
- Pumps with factory-certified pump curves
- Components used as flowmeters (terminal coils, chillers, heat exchangers, or control valves if using manufacturer's factory-certified flow versus pressure drop curves)

Record Keeping

Balancing requires accurate record keeping while making field measurements. Dated and signed field test reports help the designer or customer in work approval, and the owner has a valuable reference when documenting future changes.

Sizing Balancing Valves

A balancing valve is placed in the system to adjust water flow to a terminal, branch, zone, riser, or main. It should be located on the leaving side of the hydronic branch. General branch layout is from takeoff to entering service valve, then to the coil, control valve, and balancing/service valve. Pressure is thereby left on the coil, helping keep dissolved air in solution and preventing false balance problems resulting from air bind.

A common valve sizing method is to select for line size; however, balancing valves should be selected to pass design flows when near or at their fully open position with 12 in. of water minimum pressure drop. Larger Δp is recommended for accurate pressure readings. Many balancing valves and measuring meters give an accuracy of ±5% of range down to a pressure drop of 12 in. of water with the balancing valve wide open. Too large a balancing valve pressure drop affects the performance and flow characteristic of the control valve. Too small a pressure drop affects its flow measurement accuracy as it is closed to balance the system. Equation (2) may be used to determine the flow coefficient C_v for a balancing valve or to size a control valve.

The flow coefficient C_v is defined as the number of gallons of water per minute that flows through a wide-open valve with a pressure drop of 1 psi at 60°F. This is shown as

$$C_v = Q\sqrt{s_f/\Delta p} \qquad (2)$$

where

　Q = design flow for terminal or valve, gpm
　Δp = pressure drop, psi
　Δh = pressure drop, ft of water
　s_f = specific gravity of fluid

If pressure drop is determined in feet of water Δh, Equation (2) can be shown as

$$C_v = 1.5Q\sqrt{s_f/\Delta h} \qquad (3)$$

HYDRONIC BALANCING METHODS

Various techniques are used to balance hydronic systems. Balance by temperature difference and water balance by proportional method are the most common.

Preparation. Minimally, preparation before balancing should include collecting the following:

1. Pump submittal data; pump curves, motor data, etc.
2. Starter sizes and overload protection information
3. Control valve C_v ratings and temperature control diagrams
4. Chiller, boiler, and heat exchanger information; flow and head loss
5. Terminal unit information; flow and head loss data

6. Pressure relief and reducing valve setting
7. Flowmeter calibration curves
8. Other pertinent data

System Preparation for Static System

1. Examine piping system: Identify main pipes, risers, branches and terminals on as-built drawings. Check that flows for all balancing devices are indicated on drawings before beginning work. Check that design flows for each riser equal the sum of the design flows through the terminals.
2. Examine reducing valve
3. Examine pressure relief valves
4. Examine expansion tank
5. For pumps, confirm
   • Location and size
   • Vented volute
   • Alignment
   • Grouting
   • Motor and lubrication
   • Nameplate data
   • Pump rotational direction
6. For strainers, confirm
   • Location and size
   • Mesh size and cleanliness
7. Confirm location and size of terminal units
8. Control valves:
   • Confirm location and size
   • Confirm port locations and flow direction
   • Set all valves open to coil
   • Confirm actuator has required force to close valve under loaded conditions
9. Ensure calibration of all measuring instruments, and that all calibration data are known for balancing devices
10. Remove all air from piping; all high points should have air vents

Pump Start-Up

1. Start pump and confirm rotational direction; if rotation is incorrect, have corrected.
2. Read differential head and apply to pump curve to observe flow approximates design.
3. Slowly close pump (if pump is under 25 hp) throttle valve to shutoff. Read pump differential head from gages.
   • If shutoff head corresponds with published curve, the previously prepared velocity head correction curve can be used as a pump flow calibration curve.
   • A significant difference between observed and published shutoff head can be caused by an unvented volute, a partially plugged impeller, or by an impeller size different from that specified.

Confirmation of System Venting

1. Confirm tank location and size.
2. Shut off pump; record shutoff gauge pressure at tank junction.
3. Start pump and record operating pressure at tank junction.
4. Compare operating to shutoff pressures at tank junction. If there is no pressure change, the system is air-free.
5. Eliminate free air.
   • No air separation: Shut off pump and revent. Retest and revent until tank junction pressure is stable.
   • Air separation: Operate system until free air has been separated out, indicated by stable tank junction pressure.

Balancing

For single-, multiple-, and parallel pump systems, after pump start-up and confirmation of system venting,

1. Adjust pump throttle until pump head differential corresponds to design.
2. Record pump motor voltage and amperage, and pump strainer head, at design flow.
3. Balance equipment room piping circuit so that pumped flow remains constant over alternative flow paths.
4. Record chiller and boiler circuits (for multiple-pump systems, requires a flowmeter installed between header piping).

For multiple-pump systems only,

5. Check for variable flow in source circuits when control valves are operated.
6. Confirm
   • Pump suction pressure remains above cavitations range for all operating conditions.
   • Pump flow rates remain constant.
   • Source working pressures are unaffected.

For parallel-pump systems, follow Steps (1) to (4), then shut off pumps alternately and

5. Record head differential and flow rate through operating pump, and operating pump motor voltage and current.
6. Confirm that operational point is satisfactory (no overload, cavitation potential, etc.).

Balance by Temperature Difference

This common balancing procedure is based on measuring the water temperature difference between supply and return at the terminal. The designer selects the cooling and/or heating terminal for a calculated design load at full-load conditions. At less than full load, which is true for most operating hours, the temperature drop is proportionately less. Figure 5 demonstrates this relationship for a heating system at a design Δt of 20°F for outside design of 10°F and room design of 70°F.

For every outside temperature other than design, the balancing technician should construct a similar chart and read off the Δt for balancing. For example, at 50% load, or 30°F outside air, the Δt required is 10°F, or 50% of the design drop.

This method is a rough approximation and should not be used where great accuracy is required. It is not accurate enough for cooling systems.

Water Balance by Proportional Method

Preset Method. A thorough understanding of the pressure drops in the system riser piping, branches, coils, control valves, and balancing valves is needed. Generally, several pipe and valve sizes are
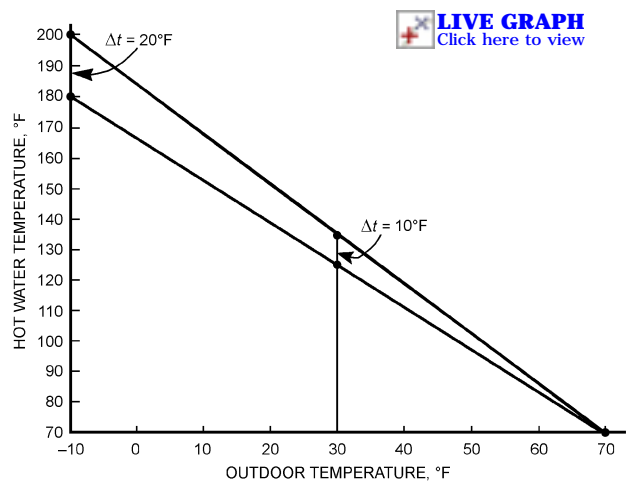
Fig. 5   Water Temperature Versus Outside Temperature Showing Approximate Temperature Difference

available for designing systems with high or low pressure drops. A flow-limiting or trim device will be required. Knowing system pressure losses in design allows the designer to select a balancing device to absorb excess system pressures in the branch, and to shift pressure drop (which might be absorbed by a balancing device nearly close to achieve balance) to the pipes, coils, and valves so the balancing device merely trims these components' performance at design flow. It may also indicate where high-head-loss circuits can exist for either relocation in the piping network, or hydraulic isolation through hybrid piping techniques. The installed balancing device should never be closed more than 40 to 50%; below this point flow reading accuracy falls to ±20 to 30%. Knowing a starting point for setting the valve (preset) allows the designer to iterate system piping design. This may not always be practical in large systems, but minimizing head and flow saves energy over the life of the facility and allows for proper temperature control. In this method,

1. Analyze the piping network for the largest hydraulic loss based on design flow and pipe friction loss. The pump should be selected to provide the total of all terminal flows, and the head required to move water through the hydraulically greatest circuit. Balance devices in this circuit should be sized only for the loss required for flow measurement accuracy. Trimming is not required.

2. Analyze differences in pressure drop in the pumping circuit for each terminal without using a balancing device. The difference between each circuit and the pump head (which represents the drop in the farthest circuit) is the required drop for the balancing device.

3. Select a balancing device that will achieve this drop with minimum valve throttling. If greater than two pipe sizes smaller, shift design drop into control valve or coil (or both), equalizing pressure drop across the devices.

4. Monitor system elevations and pressure drops to ensure air management, minimizing pocket collections and false pressure references that could lead to phantom balancing problems.

5. Use proportional balancing methods as outlined for field testing and adjustment.

Proportional Balancing

Proportional water-side balancing may use design data, but relies most on as-built conditions and measurements and adapts well to design diversity factors. This method works well with multiple-riser systems. When several terminals are connected to the same circuit, any variation of differential pressure at the circuit inlet affects flows in all other units in the same proportion. Circuits are proportionally balanced to each other by a flow quotient:

$$\text{Flow quotient} = \frac{\text{Actual flow rate}}{\text{Design flow rate}} \qquad (4)$$

To balance a branch system proportionally,

1. Fully open the balancing and control valves in that circuit.

2. Adjust the main balancing valve for total pump flow of 100 to 110% of design flow.

3. Calculate each riser valve's quotient based on actual measurements. Record these values on the test form, and note the circuit with the lowest flow quotient.

   Note: When all balancing devices are open, flow will be higher in some circuits than others. In some, flow may be so low that it cannot be accurately measured. The situation is complicated because an initial pressure drop in series with the pump is necessary to limit total flow to 100 to 110% of design; this decreases the available differential pressure for the distribution system. After all other risers are balanced, restart analysis of risers with unmeasurable flow at Step (2).

4. Identify the riser with the highest flow ratio. Begin balancing with this riser, then continue to the next highest flow ratio, and so on. When selecting the branch with the highest flow ratio,
   - Measure flow in all branches of the selected riser.
   - In branches with flow higher than 150% of design, close the balancing valves to reduce flow to about 110% of design.
   - Readjust total pump flow using the main valve.
   - Start balancing in branches with a flow ratio greater than or equal to 1. Start with the branch with the highest flow ratio.

The reference circuit has the lowest quotient and the greatest pressure loss. Adjust all other balancing valves in that branch until they have the same quotient as the reference circuit (at least one valve in the branch should be fully open).

When a second valve is adjusted, the flow quotient in the reference valve also changes; continued adjustment is required to make their flow quotients equal. Once they are equal, they will remain equal or in proportional balance to each other while other valves in the branch are adjusted or until there is a change in pressure or flow.

When all balancing valves are adjusted to their branches' respective flow quotients, total system water flow is adjusted to the design by setting the balancing valve at the pump discharge to a flow quotient of 1.

Pressure drop across the balancing valve at pump discharge is produced by the pump that is not required to provide design flow. This excess pressure can be removed by trimming the pump impeller or reducing pump speed. The pump discharge balancing valve must then be reopened fully to provide the design flow.

As in variable-speed pumping, diversity and flow changes are well accommodated by a system that has been proportionally balanced. Because the balancing valves have been balanced to each other at a particular flow (design), any changes in flow are proportionately distributed.

Balancing the water side in a system that uses diversity must be done at full flow. Because components are selected based on heat transfer at full flow, they must be balanced to this point. To accomplish full-flow proportional balance, shut off part of the system while balancing the remaining sections. When a section has been balanced, shut it off and open the section that was open originally to complete full balance of the system. When balancing, care should be taken if the building is occupied or if load is nearly full.

Variable-Speed Pumping. To achieve hydronic balance, full flow through the system is required during balancing, after which the system can be placed on automatic control and the pump speed allowed to change. After the full-flow condition is balanced and the system differential pressure set point is established, to control the variable-speed pumps, observe the flow on the circuit with the greatest resistance as the other circuits are closed one at a time. The flow in the observed circuit should remain equal to, or more than, the previously set flow. Water flow may become laminar at less than 2 fps, which may alter the heat transfer characteristics of the system.

Other Balancing Techniques

Flow Balancing by Rated Differential Procedure. This procedure depends on deriving a performance curve for the test coil, comparing water temperature difference Δt_w to entering water temperature t_{ew} minus entering air temperature t_{ea}. One point of the desired curve can be determined from manufacturer's ratings, which are published as $(t_{ew} - t_{ea})$. A second point is established by observing that the heat transfer from air to water is zero when $(t_{ew} - t_{ea})$ is zero (consequently, $\Delta t_w = 0$). With these two points, an approximate performance curve can be drawn (Figure 6). Then, for any other $(t_{ew} - t_{ea})$, this curve is used to determine the appropriate Δt_w. The basic curve applies to catalog ratings for lower dry-bulb temperatures, providing a consistent entering air moisture content (e.g., 75°F db, 65°F wb). Changes in inlet water temperature, temperature rise, air velocity, and dry- and wet-bulb temperatures cause terminal
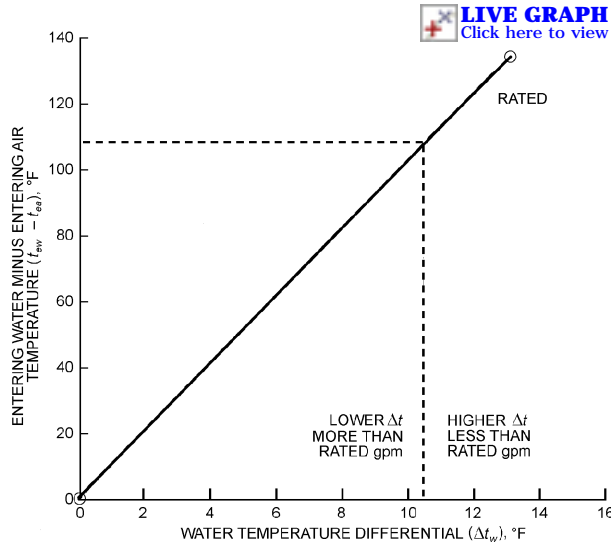
Fig. 6   Coil Performance Curve

performance to deviate from the curves. The curve may also be used for cooling coils for sensible transfer (dry coil).

Flow Balancing by Total Heat Transfer. This procedure determines water flow by running an energy balance around the coil. From field measurements of airflow, wet- and dry-bulb temperatures up- and downstream of the coil, and the difference Δt_w between entering and leaving water temperatures, water flow can be determined by the following equations:

$$Q_w = q/500 \, \Delta t_w \tag{5}$$

$$q_{cooling} = 4.5 \, Q_a(h_1 - h_2) \tag{6}$$

$$q_{heating} = 1.08 \, Q_a(t_1 - t_2) \tag{7}$$

where

Q_w = water flow rate, gpm
q = load, Btu/h
$q_{cooling}$ = cooling load, Btu/h
$q_{heating}$ = heating load, Btu/h
Q_a = airflow rate, cfm
h = enthalpy, Btu/lb
t = temperature, °F

Example 1. Find the water flow for a cooling system with the following characteristics:

Test data
t_{ewb} = entering wet-bulb temperature = 68.5°F
t_{lwb} = leaving wet-bulb temperature = 53.5°F
Q_a = airflow rate = 22,000 cfm
t_{lw} = leaving water temperature = 59.0°F
t_{ew} = entering water temperature = 47.5°F

From psychrometric chart
h_1 = 32.84 Btu/lb
h_2 = 22.32 Btu/lb

Solution: From Equations (5) and (6),

$$Q_w = \frac{4.5 \times 22,000(32.84 - 22.32)}{500(59.0 - 47.5)} = 181 \text{ gpm}$$

The desired water flow is achieved by successive manual adjustments and recalculations. Note that these temperatures can be greatly influenced by the heat of compression, stratification, bypassing, and duct leakage.

General Balance Procedures

All the variations of balancing hydronic systems cannot be listed; however, the general method should balance the system and minimize operating cost. Excess pump pressure (operating power) can be eliminated by trimming the pump impeller. Allowing excess pressure to be absorbed by throttle valves adds a lifelong operating-cost penalty to the operation.

The following is a general procedure based on setting the balance valves on the site:

1. Develop a flow diagram if one is not included in the design drawings. Illustrate all balance instrumentation, and include any additional instrument requirements.
2. Compare pumps, primary heat exchangers, and specified terminal units, and determine whether a design diversity factor can be achieved.
3. Examine the control diagram and determine the control adjustments needed to obtain design flow conditions.

Balance Procedure—Primary and Secondary Circuits

1. Inspect the system completely to ensure that (1) it has been flushed out, it is clean, and all air is removed; (2) all manual valves are open or in operating position; (3) all automatic valves are in their proper positions and operative; and (4) the expansion tank is properly charged.
2. Place controls in position for design flow.
3. Examine flow diagram and piping for obvious short circuits; check flow and adjust the balance valve.
4. Take pump suction, discharge, and differential pressure readings at both full and no flow. For larger pumps, a no-flow condition may not be safe. In any event, valves should be closed slowly.
5. Read pump motor amperage and voltage, and determine approximate power.
6. Establish a pump curve, and determine approximate flow rate.
7. If a total flow station exists, determine the flow and compare with pump curve flow.
8. If possible, set total flow about 10% high using the total flow station first and the pump differential pressure second; then maintain pumped flow at a constant value as balance proceeds by adjusting the pump throttle valve.
9. Any branch main flow stations should be tested and set, starting by setting the shortest runs low as balancing proceeds to the longer branch runs.
10. With primary and secondary pumping circuits, a reasonable balance must be obtained in the primary loop before the secondary loop can be considered. The secondary pumps must be running and terminal units must be open to flow when the primary loop is being balanced, unless the secondary loop is decoupled.

FLUID FLOW MEASUREMENT

Flow Measurement Based on Manufacturer's Data

Any component (terminal, control valve, or chiller) that has an accurate, factory-certified flow/pressure drop relationship can be used as a flow-indicating device. The flow and pressure drop may be used to establish an equivalent flow coefficient as shown in Equation (3). According to the Bernoulli equation, pressure drop varies as the square of the velocity or flow rate, assuming density is constant:

$$Q_1^2/Q_2^2 = \Delta h_1/\Delta h_2 \tag{8}$$

For example, a chiller has a certified pressure drop of 25 ft of water at 100 gpm. The calculated flow with a field-measured pressure drop of 30 ft is

$$Q_2 = 100\sqrt{30/25} = 109.5 \text{ gpm}$$

Flow calculated in this manner is only an estimate. The accuracy of components used as flow indicators depends on the accuracy of (1) cataloged information concerning flow/pressure drop relationships and (2) pressure differential readings. As a rule, the component should be factory-certified flow tested if it is to be used as a flow indicator.

Pressure Differential Readout by Gage

Gages are used to read differential pressures. Gages are usually used for high differential pressures and manometers for lower differentials. Accurate gage readout is diminished when two gages are used, especially when the gages are permanently mounted and, as such, subject to malfunction.

A single high-quality gage should be used for differential readout (Figure 7). This gage should be alternately valved to the high- and low-pressure side to establish the differential. A single gage needs no static height correction, and errors caused by gage calibration are eliminated.

Differential pressure can also be read from differential gages, thus eliminating the need to subtract outlet from inlet pressures to establish differential pressure. Differential pressure gages are usually dual gages mechanically linked to read differential pressure. The differential pressure gage readout can be stated in terms of psi or in feet of head of 60°F water.

Conversion of Differential Pressure to Head

Pressure gage readings can be restated to fluid head, which is a function of fluid density. The common hydronic system conversion factor is related to water density at about 60°F; 1 psi equals 2.31 ft. Pressure gages can be calibrated to feet of water head using this conversion. Because the calibration only applies to water at 60°F, the readout may require correction when the gage is applied to water at a significantly higher temperature.

Pressure gage conversion and correction factors for various fluid specific gravities (in relation to water at 60°F) are shown in Table 2. The differential gage readout should only be defined in terms of the head of the fluid actually causing the flow pressure differential. When this is done, the resultant fluid head can be applied to the C_v to determine actual flow through any flow device, provided the manufacturer has correctly stated the flow to fluid head relationship.

For example, a manufacturer may test a boiler or control valve with 100°F water. If the test differential pressure is converted to head at 100°F, a C_v independent of test temperature and density may be calculated. Differential pressures from another test made in the field at 250°F may be converted to head at 250°F. The C_v calculated with this head is also independent of temperature. The manufacturer's data can then be directly correlated with the field test to establish flow rate at 250°F.

A density correction must be made to the gage reading when differential heads are used to estimate pump flows as in Figure 8. This is because of the shape of the pump curve. An incorrect head difference
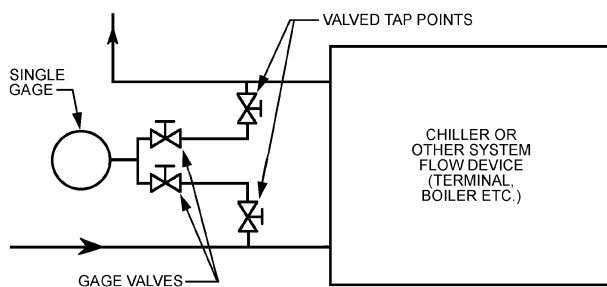
entry into the curve caused by an uncorrected gage reading can cause a major error in the estimated pumped flow. In this case, the gage reading for a pumped liquid that has a specific gravity of 0.9 (2.57 ft liquid/psi) was not corrected; the gage conversion is assumed to be 2.31 ft liquid/psi. A 50% error in flow estimation is shown.

Differential Head Readout with Manometers

Manometers are used for differential pressure readout, especially when very low differentials, great precision, or both, are required. But manometers must be handled with care; they should not be used for field testing because fluid could blow out into the water and rapidly deteriorate the components. A proposed manometer arrangement is shown in Figure 9.

Figure 9 and the following instructions provide accurate manometer readings with minimum risk of blowout.

1. Make sure that both legs of manometer are filled with water.
2. Open purge bypass valve.
3. Open valved connections to high and low pressure.
4. Open bypass vent valve slowly and purge air here.
5. Open manometer block vents and purge air at each point.
6. Close needle valves. The columns should zero in if the manometer is free of air. If not, vent again.
7. Open needle valves and begin throttling purge bypass valve slowly, watching the fluid columns. If the manometer has an adequate available fluid column, the valve can be closed and the differential reading taken. However, if the fluid column reaches the top of the manometer before the valve is completely closed, insufficient manometer height is indicated and further throttling will blow fluid into the blowout collector. A longer manometer or the single gage readout method should then be used.

An error is often introduced when converting inches of gage fluid to feet of test fluid. The conversion factor changes with test fluid temperature, density, or both. Conversion factors shown in Table 2 are to a water base, and the counterbalancing water height H (Figure 9) is at room temperature.

Orifice Plates, Venturi, and Flow Indicators

Manufacturers provide flow information for several devices used in hydronic system balance. In general, the devices can be classified as (1) orifice flowmeters, (2) venturi flowmeters, (3) velocity impact meters, (4) pitot-tube flowmeters, (5) bypass spring impact flowmeters, (6) calibrated balance valves, (7) turbine flowmeters, and (8) ultrasonic flowmeters.

The **orifice flowmeter** is widely used and is extremely accurate. The meter is calibrated and shows differential pressure versus flow. Accuracy generally increases as the pressure differential across the

Fig. 7 Single Gage for Reading Differential Pressure
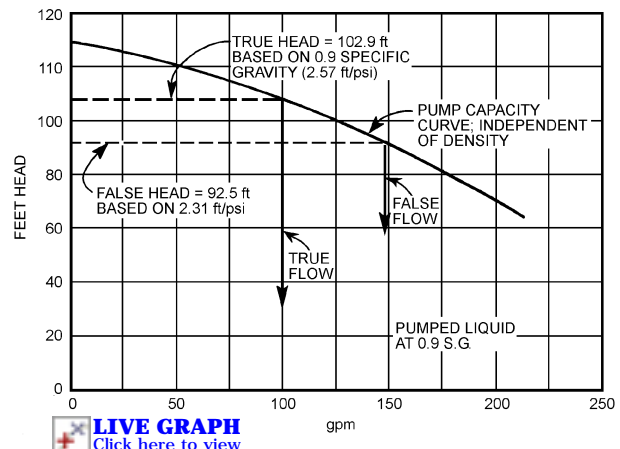
Fig. 8 Fluid Density Correction Chart for Pump Curves
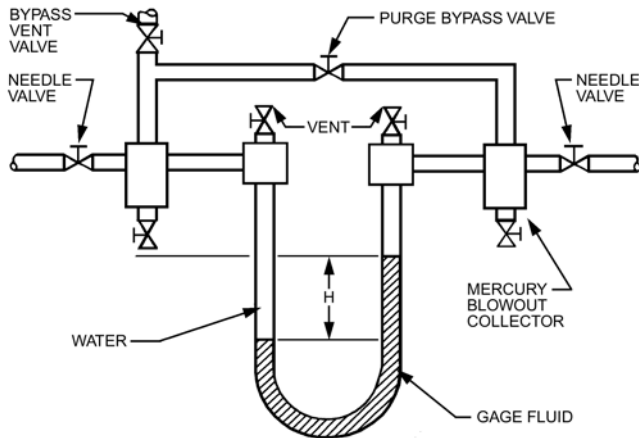
Fig. 9 Fluid Manometer Arrangement for Accurate Reading and Blowout Protection

Table 2 Differential Pressure Conversion to Head

Fluid Specific Gravity	Corresponding Water Temperature, °F	Foot Fluid Head Equal to 1 psi[a]	Correction Factor When Gage is Stated to Feet of Water (60°F)[b]
1.5		1.54	
1.4		1.65	
1.3		1.78	
1.2		1.93	
1.1		2.10	
1.0	60	2.31	1.00
0.98	150	2.36	1.02
0.96	200	2.41	1.04
0.94	250	2.46	1.065
0.92	300	2.51	1.09
0.90	340	2.57	1.11
0.80		2.89	
0.70		3.30	
0.60		3.85	
0.50		4.63	

[a]Differential psi readout is multiplied by this number to obtain feet fluid head when gage is calibrated in psi.
[b]Differential feet water head readout is multiplied by this number to obtain feet fluid head when gage calibration is stated to feet head of 60°F water.

meter increases. The differential pressure readout instrument may be a manometer, differential gage, or single gage (see Figure 7).

The **venturi flowmeter** has lower pressure loss than the orifice plate meter because a carefully formed flow path increases velocity head recovery. The venturi flowmeter is placed in a main flow line where it can be read continuously.

Velocity impact meters have precise construction and calibration. The meters are generally made of specially contoured glass or plastic, which allows observation of a flow float. As flow increases, the flow float rises in the calibrated tube to indicate flow rate. Velocity impact meters generally have high accuracy.

A special version of the velocity impact meter is applied to hydronic systems. This version operates on the velocity head difference between the pipe side wall and the pipe center, which causes fluid to flow through a small flowmeter. Accuracy depends on the location of the impact tube and on a velocity profile that corresponds to theory and the laboratory test calibration base. Generally, the accuracy of this **bypass flow impact** or differential velocity head flowmeter is less than a flow-through meter, which can operate without creating a pressure loss in the hydronic system.

The **pitot-tube flowmeter** is also used for pipe flow measurement. Manometers are generally used to measure velocity head differences because these differences are low.
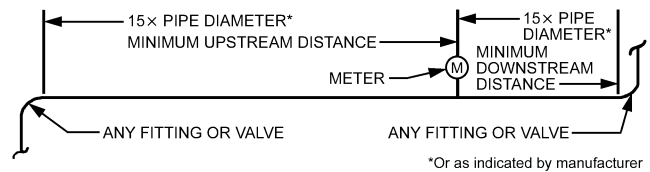
Fig. 10 Minimum Installation Dimensions for Flowmeter

The **bypass spring impact flowmeter** uses a defined piping pressure drop to cause a correlated bypass side branch flow. The side branch flow pushes against a spring that increases in length with increased flow. Each individual flowmeter is calibrated to relate extended spring length position to main flow. The bypass spring impact flowmeter has, as its principal merit, a direct readout. However, dirt on the spring reduces accuracy. The bypass is opened only when a reading is made. Flow readings can be taken at any time.

The **calibrated balance valve** is an adjustable orifice flowmeter. Balance valves can be calibrated so that a flow/pressure drop relationship can be obtained for each incremental setting of the valve. A ball, rotating plug, or butterfly valve may have its setting expressed in percent open or degree open; a globe valve, in percent open or number of turns. The calibrated balance valve must be manufactured with precision and care to ensure that each valve of a particular size has the same calibration characteristics.

The **turbine flowmeter** is a mechanical device. The velocity of the liquid spins a wheel in the meter, which generates a 4 to 20 mA output that may be calibrated in units of flow. The meter must be well maintained, because wear or water impurities on the bearing may slow the wheel, and debris may clog or break the wheel.

The **ultrasonic flowmeter** senses sound signals, which are calibrated in units of flow. The ultrasonic metering station may be installed as part of the piping, or it may be a strap-on meter. In either case, the meter has no moving parts to maintain, nor does it intrude into the pipe and cause a pressure drop. Two distinct types of ultrasonic meter are available: (1) the transit time meter for HVAC or clear-water systems and (2) the Doppler meter for systems handling sewage or large amounts of particulate matter.

If any of the above meters are to be useful, the minimum distance of straight pipe upstream and downstream, as recommended by the meter manufacturer and flow measurement handbooks, must be adhered to. Figure 10 presents minimum installation suggestions.

Using a Pump as an Indicator

Although the pump is not a meter, it can be used as an indicator of flow together with the other system components. Differential pressure readings across a pump can be correlated with the pump curve to establish the pump flow rate. Accuracy depends on (1) accuracy of readout, (2) pump curve shape, (3) actual conformance of the pump to its published curve, (4) pump operation without cavitation, (5) air-free operation, and (6) velocity head correction.

When a differential pressure reading must be taken, a single gage with manifold provides the greatest accuracy (Figure 11). The pump suction to discharge differential can be used to establish pump differential pressure and, consequently, pump flow rate. The single gage and manifold may also be used to check for strainer clogging by measuring the pressure differential across the strainer.

If the pump curve is based on fluid head, pressure differential, as obtained from the gage reading, needs to be converted to head, which is pressure divided by the fluid weight per cubic foot. The pump differential head is then used to determine pump flow rate (Figure 12). As long as the differential head used to enter the pump curve is expressed as head of the fluid being pumped, the pump curve shown by the manufacturer should be used as described. The pump curve may state that it was defined by test with 85°F water.
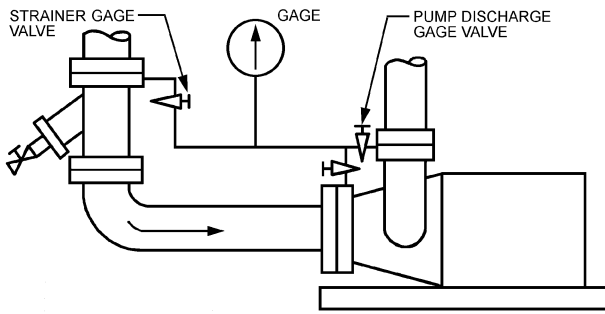
Fig. 11 Single Gage for Differential Readout Across Pump and Strainer

This is unimportant, because the same curve applies from 60 to 250°F water, or to any fluid within a broad viscosity range.

Generally, pump-derived flow information, as established by the performance curve, is questionable unless the following precautions are observed:

1. The installed pump should be factory calibrated by a test to establish the actual flow/pressure relationship for that particular pump. Production pumps can vary from the cataloged curve because of minor changes in impeller diameter, interior casting tolerances, and machine fits.
2. When a calibration curve is not available for a centrifugal pump being tested, the discharge valve can be closed briefly to establish the no-flow shutoff pressure, which can be compared to the published curve. If the shutoff pressure differs from that published, draw a new curve parallel to the published curve. Though not exact, the new curve usually fits the actual pumping circumstance more accurately. Clearance between the impeller and casing minimizes the danger of damage to the pump during a no-flow test, but manufacturer verification is necessary.
3. Differential head should be determined as accurately as possible, especially for pumps with flat flow curves.
4. The pump should be operating air-free and without cavitation. A cavitating pump will not operate to its curve, and differential readings will provide false results.
5. Ensure that the pump is operating above the minimum net positive suction head.
6. Power readings can be used (1) as a check for the operating point when the pump curve is flat or (2) as a reference check when there is suspicion that the pump is cavitating or providing false readings because of air.
7. The flow determined by the pump curve should be compared to the flow measured at the flowmeters, flow measured by pressure
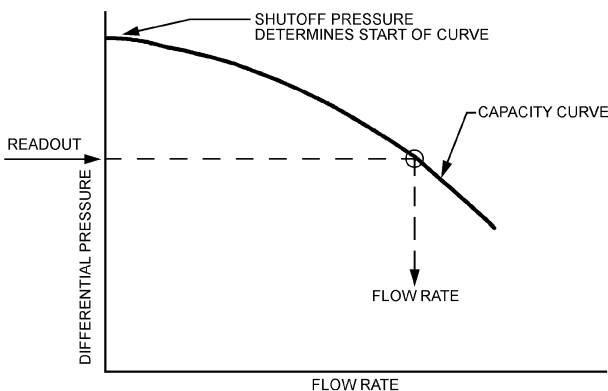
Fig. 12 Differential Pressure Used to Determine Pump Flow

drops through circuits, and flow measured by pressure drops through exchangers.
8. The pump flow derived from the pressure differential at the suction and discharge connections is only an indicator of the actual flow; it cannot be used to verify the test and balance measurements. If pump flow is to be used for balancing verification, it needs to be determined using the Hydraulic Institute procedure or by measuring the flow through a properly installed metering station 15 to 20 straight pipe diameters downstream from the pump discharge.

Power draw should be measured in watts. Ampere readings cannot be trusted because of voltage and power factor problems. If motor efficiency is known, the wattage drawn can be related to pump brake power (as described on the pump curve) and the operating point determined.

Central Plant Chilled-Water Systems

For existing installations, establishing accurate thermal load profiles is of prime importance because it establishes proper primary chilled-water supply temperature and flow. In new installations, actual load profiles can be compared with design load profiles to obtain valid operating data.

To perform proper testing and balancing, all interconnecting points between the primary and secondary systems must be designed with sufficient temperature, pressure, and flow connections so that adequate data may be indicated and/or recorded.

Water Flow Instruments

As indicated previously, proper location and use of instruments is vital to accurate balancing. Instruments for testing temperature and pressure at various locations are listed in Table 3. Flow-indicating devices should be placed in water systems as follows:

- At each major heating coil bank (10 gpm or more)
- At each major cooling coil bank (10 gpm or more)
- At each bridge in primary-secondary systems
- At each main pumping station
- At each water chiller evaporator
- At each water chiller condenser
- At each water boiler outlet
- At each floor takeoff to booster reheat coils, fan coil units, induction units, ceiling panels, and radiation (do not exceed 25 terminals off of any one zone meter probe)
- At each vertical riser to fan coil units, induction units, and radiation
- At the point of tie-in to existing systems

STEAM DISTRIBUTION

Procedures for Steam Balancing Variable Flow Systems

Steam distribution cannot be balanced by adjustable flow-regulating devices. Instead, fixed restrictions built into the piping in accordance with carefully designed pipe and orifice sizes are used to regulate flow.

It is important to have a balanced distribution of steam to all portions of the steam piping at all loads. This is best accomplished by properly designing the steam distribution piping, which includes carefully considering steam pressure, steam quantities required by each branch circuit, pressure drops, steam velocities, and pipe sizes. Just as other flow systems are balanced, steam distribution systems are balanced by ensuring that the pressure drops are equalized at design flow rates for all portions of the piping. Only marginal balancing can be done by pipe sizing. Therefore, additional steps must be taken to achieve a balanced performance.

Steam flow balance can be improved by using spring-type packless supply valves equipped with precalibrated orifices. The valves should have a tight shutoff between 25 in. of Hg and 60 psig. These valves have a nonrising stem, are available with a lockshield, and

Table 3   Instruments for Monitoring a Water System

Point of Information	Manifold Gage	Single Gage	Ther- mometer	Test Well	Pressure Tap
Pump—Suction, discharge	x				
Strainer—In, out					x
Cooler—In, out		x	x		
Condensers—In, out		x	x		
Concentrator—In, out		x	x		
Absorber—In, out		x	x		
Tower cell—In, out				x	x
Heat exchanger—In, out	x		x		
Coil—In, out				x	x
Coil bank—In, out		x	x		
Booster coil—In, out					x
Cool panel—In, out					x
Heat panel—In, out				x	x
Unit heater—In, out					x
Induction—In, out					x
Fan coil—In, out					x
Water boiler—In, out			x		
Three-way valve—All ports					x
Zone return main			x		
Bridge—In, out			x		
Water makeup		x			
Expansion tank		x			
Strainer pump					x
Strainer main	x				
Zone three-way—All ports				x	x

have a replaceable disk. Orifice flanges can also be used to regulate and measure steam flow at appropriate locations throughout the system. The orifice sizes are determined by the pressure drop required for a given flow rate at a given location. A schedule should be prepared showing (1) orifice sizes, (2) valve or pipe sizes, (3) required flow rates, and (4) corresponding pressure differentials for each flow rate. It may be useful to calculate pressure differentials for several flow rates for each orifice size. Such a schedule should be maintained for future reference.

After the appropriate regulating orifices are installed in the proper locations, the system should be tested for tightness by sealing all openings in the system and applying a vacuum of 20 in. of Hg, held for 2 hours. Next, the system should be readied for warm-up and pressurizing with steam following the procedures outlined in Section VI of the ASME *Boiler and Pressure Vessel Code*. After the initial warm-up and system pressurization, evaluate system steam flow, and compare it to system requirements. The orifice schedule calculated earlier will now be of value should any of the orifices need to be changed.

Steam Flow Measuring Devices

Many devices are available for measuring flow in steam piping: (1) steam meters, (2) condensate meters, (3) orifice plates, (4) venturi fittings, (5) steam recorders, and (6) manometers for reading differential pressures across orifice plates and venturi fittings. Some of these devices are permanently affixed to the piping system to facilitate taking instantaneous readings that may be necessary for proper operation and control. A surface pyrometer used in conjunction with a pressure gage is a convenient way to determine steam saturation temperature and the degree of superheat at various locations in the system. This information can be used to evaluate performance characteristics.

COOLING TOWERS

Field-testing cooling towers is demanding and difficult. ASME *Standard* PTC 23 and CTI *Standard Specification* ATC-105 establish procedures for these tests. Certain general guidelines for testing cooling towers are as follows:

Conditions at Time of Test
- Water flow within 15% of design

- Heat load within 30% of design and stabilized
- Entering wet bulb within 12°F of design

Using these limitations and field readings that are as accurate as possible, a projection to design conditions produces an accuracy of ±5% of tower performance.

Conditions for Performing Test
- Water-circulating systems serving tower should be thoroughly cleaned of all dirt and foreign matter. Samples of water should be clear and indicate clear passage of water through pumps, piping, screens, and strainers.
- Fans serving cooling tower should operate in proper rotation. Foreign obstructions should be removed. Permanent obstruction should be noted.
- Interior filling of cooling tower should be clean and free of foreign materials such as scale, algae, or tar.
- Water level in tower basin should be maintained at proper level. Visually check basin sump during full flow to verify that centrifugal action of the water is not causing entrainment of air, which could cause pump cavitation.
- Water-circulating pumps should be tested with full flow through tower. If flow exceeds design, it should be valved down until design is reached. The flow that is finally set should be maintained throughout the test period. All valves, except necessary balancing valves, should be fully open.
- If makeup and blowdown have facilities to determine flow, set them to design flow at full flow through the tower. If flow cannot be determined, shut off both.

Instruments

Testing and balancing agencies provide instruments to perform the required tests. Mechanical contractors provide and install all components such as orifice plates, venturis, balancing valves, thermometer wells, gage cocks, and corporation cocks. Designers specify measuring point locations.

Instruments used should be recently calibrated as follows:

Temperature
- Thermometer with divisions of 0.2°F in a proper well for water should be used.
- Thermometer with solar shield and 0.2°F divisions or thermocouple with 0.2°F readings having mechanical aspiration for wet-bulb readings should be used.
- Sling psychrometer may be used for rough checks.
- Thermometer with 0.2°F divisions should be used for dry-bulb readings.

Water Flow
- Orifice, venturi, and balancing valve pressure drops can be read using a manometer or recently calibrated differential pressure gage.
- Where corporation cocks are installed, a pitot tube and manometer traverse can be made by trained technicians.

Test Method

1. Conduct water flow tests to determine volume of water in tower, and of makeup and blowdown water.
2. Conduct water temperature tests, if possible, in suitable wells as close to tower as possible. Temperature readings at pumps or condensing element are not acceptable in tower evaluation. If there are no wells, surface pyrometer readings are acceptable.
3. Take makeup water volume and temperature readings at point of entry into tower.
4. Take blowdown volume and temperature readings at point of discharge from tower.
5. Take inlet and outlet dry- and wet-bulb temperature readings using prescribed instruments.

- Use wet-bulb entering and leaving temperatures to determine tower actual performance against design.
- Use wet- and dry-bulb entering and leaving temperatures to determine evaporation involved.

6. If tower has a ducted inlet or outlet where a reasonable duct traverse can be made, use this air volume as a cross-check of tower performance.

7. Take wet- and dry-bulb temperature readings 3 to 5 ft from the tower on all inlet sides, halfway between the base and the top of inlet louvers at no more than 5 ft spacing horizontally the readings. Note any unusual inlet conditions.

8. Note wind velocity and direction at time of test.

9. Take test readings continually with a minimum time lapse between readings.

10. If the first test indicates a tower deficiency, perform two additional tests to verify the original readings.

TEMPERATURE CONTROL VERIFICATION

The test and balance technician should work closely with the temperature control installer to ensure that the project is completed correctly. The balancing technician needs to verify proper operation of the control and communicate findings back to the agency responsible for ensuring that the controls have been installed correctly. This is usually the HVAC system designer, although others may be involved. Generally, the balancing technician does not adjust, relocate, or calibrate the controls. However, this is not always the case, and differences do occur with VAV terminal unit controllers. The balancing technician should be familiar with the specifications and design intent of the project so that all responsibilities are understood.

During the design and specification phase of the project, the designer should specify verification procedures for the controls and responsibilities for the contractor who installs the temperature controls. It is important that the designer specify the (1) degree of coordination between the installer of the control and the balancing technician and (2) testing responsibilities of each.

Verification of control operation starts with the balancing technician reviewing the submitted documents and shop drawings of the control system. In some cases, the controls technician should instruct the balancing technician in the operation of certain control elements, such as digital terminal unit controllers. This is followed by schedule coordination between the control and balancing technicians. In addition, the balancing and controls technicians need to work together when reviewing the operation of some sections of the HVAC system, particularly with VAV systems and the setting of the flow measurement parameters in digital terminal unit controllers.

Major mechanical systems should be verified after testing, adjusting, and balancing is completed. The control system should be operated in stages to prove it can match system capacity to varying load conditions. Mechanical subsystem controllers should be verified when balancing data are collected, considering that the entire system may not be completely functional at the time of verification. Testing and verification should account for seasonal variations; tests should be performed under varying outside loads to ensure operational performance. Retesting a random sample of terminal units may be desirable to verify the control technician's work.

Suggested Procedures

The following verification procedures may be used with either pneumatic or electrical controls:

1. Obtain design drawings and documentation, and become well acquainted with the design intent and specified responsibilities.
2. Obtain copies of approved control shop drawings.
3. Compare design to installed field equipment.
4. Obtain recommended operating and test procedures from manufacturers.

5. Verify with the control contractor that all controllers are calibrated and commissioned.
6. Check location of transmitters and controllers. Note adverse conditions that would affect control, and suggest relocation as necessary.
7. Note settings on controllers. Note discrepancies between set point for controller and actual measured variable.
8. Verify operation of all limiting controllers, positioners, and relays (e.g., high- and low-temperature thermostats, high- and low-differential pressure switches, etc.).
9. Activate controlled devices, checking for free travel and proper operation of stroke for both dampers and valves. Verify normally open (NO) or normally closed (NC) operation.
10. Verify sequence of operation of controlled devices. Note line pressures and controlled device positions. Correlate to air or water flow measurements. Note speed of response to step change.
11. Confirm interaction of electrically operated switch transducers.
12. Confirm interaction of interlock and lockout systems.
13. Coordinate balancing and control technicians' schedules to avoid duplication of work and testing errors.

Pneumatic System Modifications
1. Verify main control supply air pressure and observe compressor and dryer operation.
2. For hybrid systems using electronic transducers for pneumatic actuation, modify procedures accordingly.

Electronic Systems Modifications
1. Monitor voltages of power supply and controller output. Determine whether the system operates on a grounded or nongrounded power supply, and check condition. Although electronic controls now have more robust electronic circuits, improper grounding can cause functional variation in controller and actuator performance from system to system.
2. Note operation of electric actuators using spring return. Generally, actuators should be under control and use springs only upon power failure to return to a fail-safe position.

Direct Digital Controllers
Direct digital control (DDC) offers nontraditional challenges to the balancing technician. Many control devices, such as sensors and actuators, are the same as those in electronic and pneumatic systems. Currently DDC is dominated by two types of controllers: fully programmable or application-specific. Fully programmable controllers offer a group of functions linked together in an applications program to control a system such as an air-handling unit. Application-specific controllers are functionally defined with the programming necessary to carry out the functions required for a system, but not all adjustments and settings are defined. Both types of controllers and their functions have some variations. One of the functions is adaptive control, which includes control algorithms that automatically adjust settings of various controller functions.

The balancing technician must understand controller functions so that they do not interfere with the test and balance functions. Literacy in computer programming is not necessary, although it does help. When testing the DDC,

1. Obtain controller application program. Discuss application of the designer's sequence with the control programmer.
2. Coordinate testing and adjustment of controlled systems with mechanical systems testing. Avoid duplication of efforts between technicians.
3. Coordinate storage (e.g., saving to central DDC database and controller memory) of all required system adjustments with control technician.

In cases where the balancing agency is required to test discrete points in the control system,

1. Establish criteria for test with the designer.
2. Use reference standards that test the end device through the entire controller chain (e.g., device, wiring, controller, communications, and operator monitoring device). An example would be using a dry block temperature calibrator (a testing device that allows a temperature to be set, monitored, and maintained in a small chamber) to test a space temperature sensor. The sensor is installed with extra wire so that it may be removed from the wall and placed in the calibrator chamber. After the system is thermally stabilized, the temperature is read at the controller and the central monitor, if installed.
3. Report findings of reference and all points of reading.

FIELD SURVEY FOR ENERGY AUDIT

An energy audit is an organized survey of a specific building to identify and measure all energy uses, determine probable sources of energy losses, and list energy conservation opportunities. This is usually performed as a team effort under the direction of a qualified energy engineer. The field data can be gathered by firms employing technicians trained in testing, adjusting, and balancing.

Instruments

To determine a building's energy use characteristics, existing conditions must be accurately measured with proper instruments. Accurate measurements point out opportunities to reduce waste and provide a record of the actual conditions in the building before energy conservation measures were taken. They provide a compilation of installed equipment data and a record of equipment performance before changes. Judgments will be made based on the information gathered during the field survey; that which is not accurately measured cannot be properly evaluated.

Generally, instruments used for testing, adjusting, and balancing are sufficient for energy conservation surveying. Possible additional instruments include a power factor meter, light meter, combustion testing equipment, refrigeration gages, and equipment for recording temperatures, fluid flow rates, and energy use over time. Only high-quality instruments should be used.

Observation of system operation and any information the technician can obtain from the operating personnel pertaining to the operation should be included in the report.

Data Recording

Organized record keeping is extremely important. A camera is also helpful. Photographs of building components and mechanical and electrical equipment can be reviewed later when the data are analyzed.

Data sheets for energy conservation field surveys contain different and, in some cases, more comprehensive information than those used for testing, adjusting, and balancing. Generally, the energy engineer determines the degree of fieldwork to be performed; data sheets should be compatible with the instructions received.

Building Systems

The most effective way to reduce building energy waste is to identify, define, and tabulate the energy load by building system. For this purpose, load is defined as the quantity of energy used in a building, or by one of its subsystems, for a given period. By following this procedure, the most effective energy conservation opportunities can be achieved more quickly because high priorities can be assigned to systems that consume the most energy.

A building can be divided into nonenergized and energized systems. Nonenergized systems do not require outside energy sources such as electricity and fuel. Energized systems (e.g., mechanical and electrical systems) require outside energy. Energized and nonenergized systems can be divided into subsystems defined by function. Nonenergized subsystems are (1) building site, envelope, and interior; (2) building use; and (3) building operation.

Building Site, Envelope, and Interior. These subsystems should be surveyed to determine how they can be modified to reduce the building load that the mechanical and electrical systems must meet without adversely affecting the building's appearance. It is important to compare actual conditions with conditions assumed by the designer, so that mechanical and electrical systems can be adjusted to balance their capacities to satisfy actual needs.

Building Use. These loads can be classified as people occupancy or operation loads. People occupancy loads are related to schedule, density, and mixing of occupancy types (e.g., process and office). People operation loads are varied and include (1) operation of manual window shading devices; (2) setting of room thermostats; and (3) conservation-related habits such as turning off lights, closing doors and windows, turning off energized equipment when not in use, and not wasting domestic hot or chilled water.

Building Operation. This subsystem consists of the operation and maintenance of all the building subsystems. The load on the building operation subsystem is affected by factors such as (1) the time at which janitorial services are performed, (2) janitorial crew size and time required to clean, (3) amount of lighting used to perform janitorial functions, (4) quality of equipment maintenance program, (5) system operational practices, and (6) equipment efficiencies.

Building Energized Systems

The energized subsystems of the building are generally plumbing, heating, ventilating, cooling, space conditioning, control, electrical, and food service. Although these systems are interrelated and often use common components, logical organization of data requires evaluating the energy use of each subsystem as independently as possible. In this way, proper energy conservation measures for each subsystem can be developed.

Process Loads

In addition to building subsystem loads, the process load in most buildings must be evaluated by the energy field auditor. Most tasks not only require energy for performance, but also affect the energy consumption of other building subsystems. For example, if a process releases large amounts of heat to the space, the process consumes energy and also imposes a large load on the cooling system.

Guidelines for Developing a Field Study Form

A brief checklist follows that outlines requirements for a field study form needed to conduct an energy audit.

Inspection and Observation of All Systems. Record physical and mechanical condition of the following:

- Fan blades, fan scroll, drives, belt tightness, and alignment
- Filters, coils, and housing tightness
- Ductwork (equipment room and space, where possible)
- Strainers
- Insulation ducts and piping
- Makeup water treatment and cooling tower

Interview of Physical Plant Supervisor. Record answers to the following survey questions:

- Is the system operating as designed? If not, what changes have been made to ensure its performance?
- Have there been modifications or additions to the system?
- If the system has had a problem, list problems by frequency of occurrence.
- Are any systems cycled? If so, which systems and when, and would building load allow cycling systems?

Recording System Information. Record the following system/equipment identification:

- Type of system: single-zone, multizone, double-duct, low- or high-velocity, reheat, variable-volume, or other

- System arrangement: fixed minimum outside air, no relief, gravity or power relief, economizer gravity relief, exhaust return, or other
- Air-handling equipment: fans (supply, return, and exhaust) manufacturer, model, size, type, and class; dampers (vortex, scroll, or discharge); motors manufacturer, power requirement, full load amperes, voltage, phase, and service factor
- Chilled- and hot-water coils: area, tubes on face, fin spacing, and number of rows (coil data necessary when shop drawings are not available)
- Terminals: high-pressure mixing box manufacturer, model, and type (reheat, constant-volume, variable-volume, induction); grilles, registers, and diffusers manufacturer, model, style, and loss coefficient to convert field-measured velocity to flow rate
- Main heating and cooling pumps, over 5 hp: manufacturer, pump service and identification, model, size, impeller diameter, speed, flow rate, head at full flow, and head at no flow; motor data (power, speed, voltage, amperes, and service factor)
- Refrigeration equipment: chiller manufacturer, type, model, serial number, nominal tons, brake horsepower, total heat rejection, motor (horsepower, amperes, volts), chiller pressure drop, entering and leaving chilled water temperatures, condenser pressure drop, condenser entering and leaving water temperatures, running amperes and volts, no-load running amperes and volts
- Cooling tower: manufacturer, size, type, nominal tons, range, flow rate, and entering wet-bulb temperature
- Heating equipment: boiler (small through medium) manufacturer, fuel, energy input (rated), and heat output (rated)

    Recording Test Data. Record the following test data:

- Systems in normal mode of operation (if possible): fan motor running amperes and volts and power factor (over 5 hp); fan speed, total air (pitot-tube traverse where possible), and static pressure (discharge static minus inlet total); static profile drawing (static pressure across filters, heating coil, cooling coil, and dampers); static pressure at ends of runs of the system (identifying locations)
- Cooling coils: entering and leaving dry- and wet-bulb temperatures, entering and leaving water temperatures, coil pressure drop (where pressure taps permit and manufacturer's ratings can be obtained), flow rate of coil (when other than fan), outside wet and dry bulb, time of day, and conditions (sunny or cloudy)
- Heating coils: entering and leaving dry-bulb temperatures, entering and leaving water temperatures, coil pressure drop (where pressure taps permit and manufacturer's ratings can be obtained), and flow rate through coil (when other than fan)
- Pumps: no-flow head, full-flow discharge pressure, full-flow suction pressure, full-flow differential pressure, motor running amperes and volts, and power factor (over 5 hp)
- Chiller (under cooling load conditions): chiller pressure drop, entering and leaving chilled water temperatures, condenser pressure drop, entering and leaving condenser water temperatures, running amperes and volts, no-load running amperes and volts, chilled water on and off, and condenser water on and off
- Cooling tower: water flow rate in tower, entering and leaving water temperatures, entering and leaving wet bulb, fan motor [amperes, volts, power factor (over 5 hp), and ambient wet bulb]
- Boiler (full fire): input energy (if possible), percent CO_2, stack temperature, efficiency, and complete Orsat test on large boilers
- Boiler controls: description of operation
- Temperature controls: operating and set point temperatures for mixed air controller, leaving air controller, hot-deck controller, cold-deck controller, outside reset, interlock controls, and damper controls; description of complete control system and any malfunctions
- Outside air intake versus exhaust air: total airflow measured by pitot-tube traverses of both outside air intake and exhaust air systems, where possible. Determine whether an imbalance in the exhaust system causes infiltration. Observe exterior walls to

determine whether outside air can infiltrate return air (record outside air, return air, and return air plenum dry- and wet-bulb temperatures). The greater the differential between outside and return air, the more evident the problem will be.

REPORTS

The report is a record of the HVAC system balancing and must be accurate in all respects. If the data are incomplete, it must be listed as a deficiency for correction by the installing contractor.

Reports should comply with ASHRAE *Standard* 111, be complete, and include the location of test drawings. An instrument list including serial numbers and current and future calibration dates should also be provided.

TESTING FOR SOUND AND VIBRATION

Testing for sound and vibration ensures that equipment is operating satisfactorily and that no objectionable noise and vibration are transmitted to the building structure and occupied space. Although sound and vibration are specialized fields that require expertise not normally developed by the HVAC engineer, the procedures to test HVAC are relatively simple and can be performed with a minimum of equipment by following the steps outlined in this section. Although this section provides useful information for resolving common noise and vibration problems, Chapter 47 should be consulted for information on problem solving or the design of HVAC.

Testing for Sound

Present technology does not test whether equipment is operating with desired sound levels; field tests can only determine sound pressure levels, and equipment ratings are almost always in terms of sound power levels. Until new techniques are developed, the testing engineer can only determine (1) whether sound pressure levels are within desired limits and (2) which equipment, systems, or components are the source of excessive or disturbing transmission.

Sound-Measuring Instruments. Although an experienced listener can often determine whether systems are operating in an acceptably quiet manner, sound-measuring instruments are necessary to determine whether system noise levels are in compliance with specified criteria, and if not, to obtain and report detailed information to evaluate the cause of noncompliance. Instruments normally used in field testing are as follows.

The **precision sound level meter** is used to measure sound pressure level. The most basic sound level meters measure overall sound pressure level and have up to three weighted scales that provide limited filtering capability. The instrument is useful in assessing outside noise levels in certain situations and can provide limited information on the low-frequency content of overall noise levels, but it provides insufficient information for problem diagnosis and solution. Its usefulness in evaluating indoor HVAC sound sources is thus limited.

Proper evaluation of HVAC sound sources requires a sound level meter capable of filtering overall sound levels into frequency increments of one octave or less.

Sound analyzers provide detailed information about sound pressure levels at various frequencies through filtering networks. The most popular sound analyzers are the octave band and center frequency, which break the sound into the eight octave bands of audible sound. Instruments are also available for 0.33, 0.1, and narrower spectrum analysis; however, these are primarily for laboratory and research applications. Sound analyzers (octave midband or center frequency) are required where specifications are based on noise criteria (NC) and room criteria (RC) curves or similar frequency criteria and for problem jobs where a knowledge of frequency is necessary to determine proper corrective action.

Personal computers are a versatile sound-measuring tool. Software used on portable computers has all the functional capabilities

described previously, plus many that previously required a fully equipped acoustical laboratory. This type of sound-measuring system is many times faster and much more versatile than conventional sound level meters. With suitable accessories, it can also be used to evaluate vibration levels. Accuracy and calibration to applicable standards are of concern for software.

Regardless of which sound-measuring system is used, it should be calibrated before each use. Some systems have built-in calibration, while others use external calibrators. Much information is available on the proper application and use of sound-measuring instruments.

Air noise, caused by air flowing at a velocity of over 1000 fpm or by winds over 12 mph, can cause substantial error in sound measurements because of wind effect on the microphone. For outside measurements or in drafty places, either a wind screen for the microphone or a special microphone is required. When in doubt, use a wind screen on standard microphones.

Sound Level Criteria. Without specified values, the testing engineer must determine whether sound levels are within acceptable limits (Chapter 47). Note that complete absence of noise is seldom a design criterion, except for certain critical locations such as sound and recording studios. In most locations, a certain amount of noise is desirable to mask other noises and provide speech privacy; it also provides an acoustically pleasing environment, because few people can function effectively in extreme quiet. Table 1 in Chapter 7 of the 2005 *ASHRAE Handbook—Fundamentals* lists typical sound pressure levels. In determining allowable HVAC equipment noise, it is as inappropriate to demand 30 dB for a factory where the normal noise level is 75 dB as it is to specify 60 dB for a private office where the normal noise level might be 35 dB.

Most field sound-measuring instruments and techniques yield an accuracy of ±3 dB, the smallest difference in sound pressure level that the average person can discern. A reasonable tolerance for sound criteria is 5 dB; if 35 dBA is considered the maximum allowable noise, the design engineer should specify 30 dBA.

The measured sound level of any location is a combination of all sound sources present, including sound generated by HVAC equipment as well as sound from other sources such as plumbing systems and fixtures, elevators, light ballasts, and outside noises. In testing for sound, all sources from other than HVAC equipment are considered background or ambient noise.

Background sound measurements generally have to be made (1) when the specification requires that the sound levels from HVAC equipment only, as opposed to the sound level in a space, not exceed a certain specified level; (2) when the sound level in the space exceeds a desirable level, in which case the noise contributed by the HVAC system must be determined; and (3) in residential locations where little significant background noise is generated during the evening hours and where generally low allowable noise levels are specified or desired. Because background noise from outside sources such as vehicular traffic can fluctuate widely, sound measurements for residential locations are best made in the normally quiet evening hours. Procedures for residential sound measurements can be found in ASTM *Standard* E1574, Measurement of Sound in Residential Spaces.

Sound Testing. Ideally, a building should be completed and ready for occupancy before sound level tests are taken. All spaces in which readings will be taken should be furnished with whatever drapes, carpeting, and furniture are typical because these affect the room absorption, which can affect sound levels and the subjective quality of the sound. In actual practice, because most tests must be conducted before the space is completely finished and furnished for final occupancy, the testing engineer must make some allowances. Because furnishings increase the absorption coefficient and reduce by about 4 dB the sound pressure level that can be expected between most live and dead spaces, the following guidelines should suffice for measurements made in unfurnished spaces. If the sound pressure level is 5 dB or more over the specified or desired criterion, it can be

assumed that the criterion will not be met, even with the increased absorption provided by furnishings. If the sound pressure level is 0 to 4 dB greater than the specified or desired criterion, recheck when the room is furnished to determine compliance.

Follow this general procedure:

1. Obtain a complete set of accurate, as-built drawings and specifications, including duct and piping details. Review specifications to determine sound and vibration criteria and any special instructions for testing.
2. Visually check for noncompliance with plans and specifications, obvious errors, and poor workmanship. Turn system on for aural check. Listen for noise and vibration, especially duct leaks and loose fittings.
3. Adjust and balance equipment, as described in other sections, so that final acoustical tests are made with the HVAC as it will be operating. It is desirable to perform acoustical tests for both summer and winter operation, but where this is not practical, make tests for the summer operating mode, as it usually has the potential for higher sound levels. Tests must be made for all mechanical equipment and systems, including standby.
4. Check calibration of instruments.
5. Measure sound levels in all areas as required, combining measurements as indicated in step 3 if equipment or systems must be operated separately. Before final measurements are made in any particular area, survey the area using an A-weighted scale reading (dBA) to determine the location of the highest sound pressure level. Indicate this location on a testing form, and use it for test measurements. Restrict the preliminary survey to determine location of test measurements to areas that can be occupied by standing or sitting personnel. For example, measurements would not be made directly in front of a diffuser located in the ceiling, but would be made as close to the diffuser as standing or sitting personnel might be situated. In the absence of specified sound criteria, the testing engineer should measure sound pressure levels in all occupied spaces to determine compliance with criteria indicated in Chapter 47 and to locate any sources of excessive or disturbing noise. With octave band sound level measurements, overall NC and RC values can be determined. Measurements of 63 to 8000 Hz should be considered the minimum when sound levels in the 16 and 31.5 Hz octave band are desired, from completeness and evaluation of the possibility of noise-induced vibration as evaluated by RC and NCB methods.
6. Determine whether background noise measurements must be made.
   - If specification requires determining sound level from HVAC equipment only, background noise readings must be taken with HVAC equipment turned off.
   - If specification requires compliance with a specific noise level or criterion (e.g., sound levels in office areas not to exceed 35 dBA), ambient noise measurements must be made only if the noise level in any area exceeds the specified value.
   - For residential locations and areas requiring very low noise, such as sound recording studios and locations used during the normally quieter evening hours, it is usually desirable to take sound measurements in the evening and/or take ambient noise measurements.
7. For outside noise measurements to determine noise radiated by outside or roof-mounted equipment such as cooling towers and condensing units, the section on Sound Control for Outdoor Equipment in Chapter 47, which presents proper procedure and necessary calculations, should be consulted.

Noise Transmission Problems. Regardless of precautions taken by the specifying engineer and installing contractors, situations can occur where the sound level exceeds specified or desired levels, and there will be occasional complaints of noise in completed installations. A thorough understanding of Chapter 47 and the section on

Testing for Vibration in this chapter is desirable before attempting to resolve any noise and vibration transmission problems. The following is intended as an overall guide rather than a detailed problem-solving procedure.

All noise transmission problems can be evaluated in terms of the source-path-receiver concept. Objectionable transmission can be resolved by (1) reducing noise at the source by replacing defective equipment, repairing improper operation, proper balancing and adjusting, and replacing with quieter equipment; (2) attenuating paths of transmission with silencers, vibration isolators, and wall treatment to increase transmission loss; and (3) reducing or masking objectionable noise at the receiver by increasing room absorption or introducing a nonobjectionable masking sound. The following discussion includes ways to identify actual noise sources using simple instruments or no instruments and possible corrections.

When troubleshooting in the field, the engineer should listen to the offending sound. The best instruments are no substitute for careful listening, because the human ear has the remarkable ability to identify certain familiar sounds such as bearing squeak or duct leaks and can discern small changes in frequency or sound character that might not be apparent from meter readings only. The ear is also a good direction and range finder; noise generally gets louder as one approaches the source, and direction can often be determined by turning the head. Hands can also identify noise sources. Air jets from duct leaks can often be felt, and the sound of rattling or vibrating panels or parts often changes or stops when these parts are touched.

In trying to locate noise sources and transmission paths, the engineer should consider the location of the affected area. In areas remote from equipment rooms containing significant noise producers but adjacent to shafts, noise is usually the result of structure-borne transmission through pipe and duct supports and anchors. In areas adjoining, above, or below equipment rooms, noise is usually caused by openings (acoustical leaks) in the separating floor or wall or by improper, ineffective, or maladjusted vibration isolation systems.

Unless the noise source or path of transmission is quite obvious, the best way to identify it is by eliminating all sources systematically as follows:

1. Turn off all equipment to make sure that the objectionable noise is caused by the HVAC. If the noise stops, the HVAC components (compressors, fans, and pumps) must be operated separately to determine which are contributing to the objectionable noise. Where one source of disturbing noise predominates, the test can be performed starting with all equipment in operation and turning off components or systems until the disturbing noise is eliminated. Tests can also be performed starting with all equipment turned off and operating various component equipment singularly, which permits evaluation of noise from each individual component.

   Any equipment can be termed a predominant noise source if, when the equipment is shut off, the sound level drops 3 dBA or if, when measurements are taken with equipment operating individually, the sound level is within 3 dBA of the overall objectionable measurement.

   When a sound level meter is not used, it is best to start with all equipment operating and shut off components one at a time because the ear can reliably detect differences and changes in noise but not absolute levels.

2. When some part of the HVAC system is established as the source of objectionable noise, try to further isolate the source. By walking around the room, determine whether the noise is coming through air outlets or returns, hung ceiling, or floors or walls.

3. If the noise is coming through the hung ceiling, check that ducts and pipes are isolated properly and not touching the hung ceiling supports or electrical fixtures, which would provide large noise radiating surfaces. If ducts and pipes are the source of noise and are isolated properly, possible remedies to reduce noise include

changing flow conditions, installing silencers, and/or wrapping the duct or pipe with an acoustical barrier or lagging such as a lead blanket or other materials suitable for the location (see Chapter 47).

4. If noise is coming through the walls, ceiling, or floor, check for any openings to adjoining shafts or equipment rooms, and check vibration isolation systems to ensure that there is no structure-borne transmission from nearby equipment rooms or shafts.

5. Noise traced to air outlets or returns usually requires careful evaluation by an engineer or acoustical consultant to determine the source and proper corrective action (see Chapter 47). In general, air outlets can be selected to meet any acoustical design goal by keeping the velocity sufficiently low. For any given outlet, the sound level increases about 2 dB for each 10% increase in airflow velocity over the vanes, and doubling the velocity increases the sound level by about 12 to 15 dB. Approach conditions caused by improperly located control dampers or improperly sized diffuser necks can increase sound levels by 10 to 20 dB. Using variable-frequency drive (VFD) speed controllers on air-handling units can help evaluate air velocity concerns. Dampers used to limit airflow often influence overall sound levels.

   A simple, effective instrument that aids in locating noise sources is a microphone mounted on a pole. It can be used to localize noises in hard-to-reach places, such as hung ceilings and behind heavy furniture.

6. If noise is traced to an air outlet, measure the A-weighted sound level close to it but with no air blowing against the microphone. Then, remove the inner assembly or core of the air outlet and repeat the reading with the meter and the observer in exactly the same position as before. If the second reading is more than 3 dB below the first, a significant amount of noise is caused by airflow over the vanes of the diffuser or grille. In this case, check whether the system is balanced properly. As little as 10% too much air increases the sound generated by an air outlet by 2.5 dB. As a last resort, a larger air outlet could be substituted to obtain lower air velocities and hence less turbulence for the same air quality. Before this is considered, however, the air approach to the outlet should be checked.

   Noise far exceeding the normal rating of a diffuser or grille is generated when a throttled damper is installed close to it. Air jets impinge on the vanes or cones of the outlet and produce **edge tones** similar to the hiss heard when blowing against the edge of a ruler. The material of the vanes has no effect on this noise, although loose vanes may cause additional noise from vibration.

   When balancing air outlets with integral volume dampers, consider the static pressure drop across the damper, as well as the air quantity. Separate volume dampers should be installed sufficiently upstream from the outlet that there is no jet impingement. Plenum inlets should be brought in from the side, so that jets do not impinge on the outlet vanes.

7. If air outlets are eliminated as sources of excessive noise, inspect the fan room. If possible, change fan speed by about 10%. If resonance is involved, this small change can make a significant difference.

8. Sometimes fans are poorly matched to the system. If a belt-driven fan delivers air at a higher static pressure than is needed to move the design air quantity through the system, reduce fan speed by changing sheaves. If the fan does not deliver enough air, consider increasing fan speed only after checking the duct system for unavoidable losses. Turbulence in the air approach to the fan inlet increases fan sound generation and decreases its air capacity. Other parts that may cause excessive turbulence are dampers, duct bends, and sudden enlargements or contractions of the duct. When investigating fan noise, seek assistance from the fan supplier or manufacturer.

9. If additional acoustical treatment is to be installed in the duct-work, obtain a frequency analysis. This involves the use of an octave-band analyzer and should generally be left to a trained engineer or acoustic analysis consultant.

Testing for Vibration

Vibration testing is necessary to ensure that (1) equipment is operating within satisfactory vibration levels and (2) objectionable vibration and noise are not transmitted to the building structure. Although these two factors are interrelated, they are not necessarily interdependent. A different solution is required for each, and it is essential to test both the isolation and vibration levels of equipment.

General Procedure.

1. Make a visual check of all equipment for obvious errors that must be corrected immediately.
2. Make sure all isolation is free-floating and not short-circuited by obstruction between equipment or equipment base and building structure.
3. Turn on the system for an aural check of any obviously rough operation. Checking bearings with vibration measurement instrumentation is especially important because bearings can become defective in transit and/or if equipment was not properly stored, installed, or maintained. Defective bearings should be replaced immediately to avoid damage to the shaft and other components.
4. Adjust and balance equipment and systems so that final vibration tests are made on equipment as it will actually be operating.
5. Test equipment vibration.

Instruments. Although instruments are not required to test vibration isolation systems, they are essential to test equipment vibration properly.

Sound-level meters and **computer-driven sound-measuring systems** are the most useful instruments for measuring and evaluating vibration. Usually, they are fitted with accelerometers or vibration pickups for a full range of vibration measurement and analysis. Other instruments used for testing vibration in the field are described as follows.

Reed vibrometers are relatively inexpensive and are often used for testing vibration, but their relative inaccuracy limits their usefulness.

Vibrometers are moderately priced and measure vibration amplitude by means of a light beam projected on a graduated scale.

Vibrographs are moderately priced mechanical instruments that measure both amplitude and frequency. They provide a chart recording amplitude, frequency, and actual wave form of vibration. They can be used for simple, accurate determination of the natural frequency of shafts, components, and systems by a **bump test**.

Reed vibrometers, vibrometers, and vibrographs have largely been supplanted by electronic meters that are more accurate and have become much more affordable.

Vibration meters are moderately priced, relatively simple-to-use modern electronic instruments that measure the vibration amplitude. They provide a single broadband (summation of all frequencies) number identifying the magnitude of the vibration level. Both analog and digital readouts are common.

Vibration analyzers are relatively expensive electronic instruments that measure amplitude and frequency, usually incorporating a variable filter.

Strobe lights are often used with many of the other instruments for analyzing and balancing rotating equipment.

Stethoscopes are available as inexpensive mechanic's type (basically, a standard stethoscope with a probe attachment), relatively inexpensive models incorporating a tunable filter, and moderately priced powered types that electronically amplify sound and provide some type of meter and/or chart recording.

The choice of instruments depends on the test. Vibrometers and vibration meters can be used to measure vibration amplitude as an acceptance check. Because they cannot measure frequency, they cannot be used for analysis and primarily function as a go/no-go instrument. The best acceptance criteria consider both amplitude and frequency. Anyone seriously concerned with vibration testing should use an instrument that can determine frequency as well as amplitude, such as a vibrograph or vibration analyzer.

Vibration measurement instruments (both meters and analyzers) made specifically for measuring machinery vibration typically use **moving coil velocity transducers**, which are sizable and rugged. These are typically limited to a lower frequency of 500 cycles per minute (cpm) [8.33 Hz] with normal calibration. If measuring very-low-speed machinery such as large fans, cooling towers, or compressors operating below this limit, use an adjustment factor provided by the instrument manufacturer or use an instrument with a lower low-frequency limit, which typically uses a smaller accelerometer as the vibration pickup transducer.

Testing Vibration Isolation.

1. Ensure that equipment is **free-floating** by applying an unbalanced load, which should cause the equipment to move freely and easily. On floor-mounted equipment, check that there are no obstructions between the base or foundation and the building structure that would cause transmission while still permitting equipment to rock relatively free because of the application of an unbalanced force (Figure 13). On suspended equipment, check that hanger rods are not touching the hanger. Rigid connections such as pipes and ducts can prohibit mounts from functioning properly and from providing a transmission path. Note that the fact that the equipment is free floating does not mean that the isolators are functioning properly. For example, a 500 rpm fan on isolators with a natural frequency of 500 cpm (8.33 Hz) could be free-floating but would actually be in resonance, resulting in transmission to the building and excessive movement.
2. Determine whether isolators are adjusted properly and providing desired isolation efficiency. All isolators supporting a piece of equipment should have approximately the same deflection (i.e., they should be compressed the same under the equipment). If not, they have been improperly adjusted, installed, or selected; this should be corrected immediately. Note that isolation efficiency cannot be checked by comparing vibration amplitude on equipment to amplitude on the structure (Figure 14).

The only accurate check of isolation efficiencies is to compare vibration measurements of equipment operating with isolators to measurements of equipment operating without isolators. Because this is usually impractical, it is better to check whether the isolator's deflection is as specified and whether the specified or desired isolation efficiency is being provided. Figure 15 shows natural frequency of isolators as a function of deflection and indicates the theoretical isolation efficiencies for various frequencies at which the equipment operates.

Although it is easy to determine the deflection of spring mounts by measuring the difference between the free heights with a ruler (information as shown on submittal drawings or available from a manufacturer), these measurements are difficult with most pad or rubber mounts. Further, most pad and rubber mounts do not lend themselves to accurate determination of natural frequency as a func-
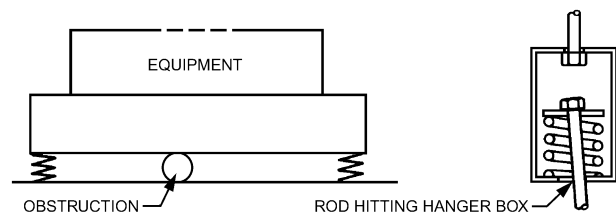
Fig. 13 Obstructed Isolation Systems

tion of deflection. For these mounts, the most practical approach is to check that there is no excessive vibration of the base and no noticeable or objectionable vibration transmission to the building structure.

If isolators are in the 90% efficiency range and there is transmission to the building structure, either the equipment is operating roughly or there is a flanking path of transmission, such as connecting piping or obstruction, under the base.

Testing Equipment Vibration. Testing equipment vibration is necessary as an acceptance check to determine whether equipment is functioning properly and to ensure that objectionable vibration and noise are not transmitted. Although a person familiar with equipment can determine when it is operating roughly, instruments are usually required to determine accurately whether vibration levels are satisfactory.

Vibration Tolerances. Vibration tolerance criteria are listed in Table 46 of Chapter 47. These criteria are based on equipment installed on vibration isolators and can be met by any reasonably smoothly running equipment. Note that values in Chapter 47 are based on root-mean-square (RMS) values; other sources often use peak-to-peak or peak values, especially for displacements. For sinusoid responses, it is simple to obtain peak from RMS values, but in application the relationship may not be so straightforward. The main advantage of RMS is that the same instrumentation can be used for both sound and vibration measurements by simply changing the transducer. Also, there is only one recognized reference level for the deci-
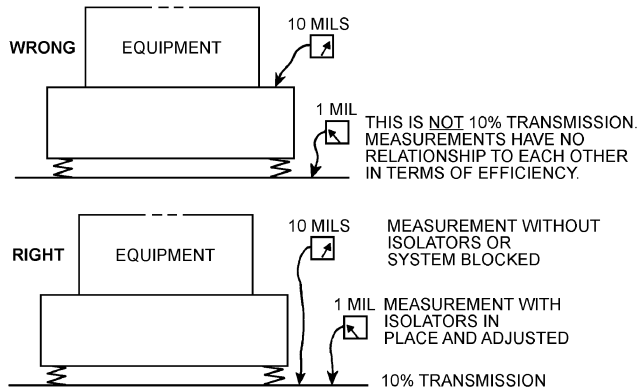
Fig. 14   Testing Isolation Efficiency
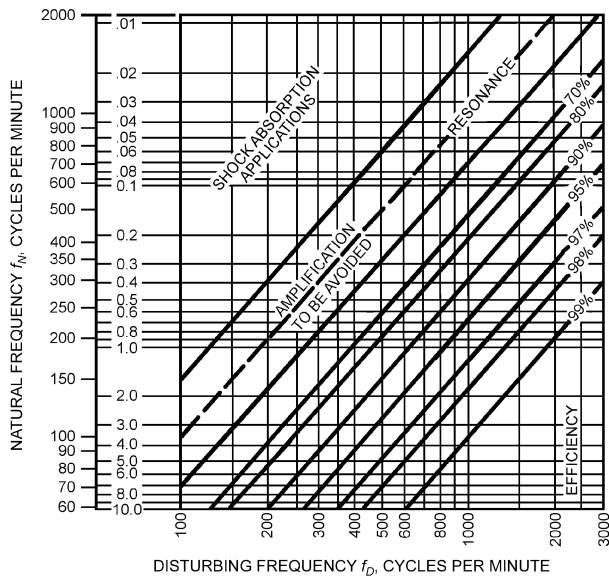
Fig. 15   Isolator Natural Frequencies and Efficiencies

bel used for sound-pressure levels, but for vibration levels there are several recognized ones but no single standard. A common mistake in interpreting vibration data is misunderstanding the reference level and whether the vibration data are RMS, peak-to-peak, or peak values. Use great care in publishing and interpreting vibration data and converting to and from linear absolute values and levels in decibels.

Procedure for Testing Equipment Vibration.

1. Determine operating speeds of equipment from nameplates, drawings, or a speed-measuring device such as a tachometer or strobe, and indicate them on the test form. For any equipment where the driving speed (motor) is different from the driven speed (fan wheel, rotor, impeller) because of belt drive or gear reducers, indicate both driving and driven speeds.
2. Determine acceptance criteria from specifications, and indicate them on the test form. If specifications do not provide criteria, use those shown in Chapter 47.
3. Ensure that the vibration isolation system is functioning properly (see the section on Testing Vibration Isolation).
4. Operate equipment and make visual and aural checks for any apparent rough operation. Any defective bearings, misalignment, or obvious rough operation should be corrected before proceeding further. If not corrected, equipment should be considered unacceptable.
5. Measure and record vibration at bearings of driving and driven components in horizontal, vertical, and, if possible, axial directions. At least one axial measurement should be made for each rotating component (fan motor, pump motor).
6. Evaluate measurements.

Evaluating Vibration Measurements.

Amplitude Measurement. When specification for acceptable equipment vibration is based on amplitude measurements only, and measurements are made with an instrument that measures only amplitude (e.g., a vibration meter or vibrometer),

• No measurement should exceed specified values or values shown in Tables 46 or 47 of Chapter 47, taking into consideration reduced values for equipment installed on inertia blocks
• No measurement should exceed values shown in Tables 46 or 47 of Chapter 47 for driving and driven speeds, taking into consideration reduced values for equipment installed on inertia blocks. For example, with a belt-driven fan operating at 800 rpm and having an 1800 rpm driving motor, amplitude measurements at fan bearings must be in accordance with values shown for 800 cpm (13.3 Hz), and measurements at motor bearings must be in accordance with values shown for 1800 cpm (30 Hz). If measurements at motor bearings exceed specified values, take measurements of the motor only with belts removed to determine whether there is feedback vibration from the fan.
• No axial vibration measurement should exceed maximum radial (vertical or horizontal) vibration at the same location.

Amplitude and Frequency Measurement. When specification for acceptable equipment vibration is based on both amplitude and frequency measurements, and measurements are made with instruments that measure both amplitude and frequency (e.g., a vibrograph or vibration analyzer),

• Amplitude measurements at driving and driven speeds should not exceed specified values or values shown in Tables 46 or 47 of Chapter 47, taking into consideration reduced values for equipment installed on inertia blocks. Measurements that exceed acceptable amounts may be evaluated as explained in the section on Vibration Analysis.
• Axial vibration measurements should not exceed maximum radial (vertical or horizontal) vibration at the same location.
• The presence of any vibration at frequencies other than driving or driven speeds is generally reason to rate operation unacceptable;

this vibration should be analyzed as explained in the section on Vibration Analysis.

Vibration Analysis. The following guide covers most vibration problems that may be encountered.

Axial Vibration Exceeds Radial Vibration. When the amplitude of axial vibration (parallel with shaft) at any bearing exceeds radial vibration (perpendicular to shaft, vertical or horizontal), it usually indicates misalignment, most common on direct-driven equipment because flexible couplings accommodate parallel and angular misalignment of shafts. This misalignment can generate forces that cause axial vibration, which can cause premature bearing failure, so misalignment should be checked carefully and corrected promptly. Other possible causes of large-amplitude axial vibration are resonance, defective bearings, insufficient rigidity of bearing supports or equipment, and loose hold-down bolts.

Vibration Amplitude Exceeds Allowable Tolerance at Rotational Speed. The allowable vibration limits established by Table 38 of Chapter 47 are based on vibration caused by rotor imbalance, which results in vibration at rotational frequency. Although vibration caused by imbalance must be at the frequency at which the part is rotating, a vibration at rotational frequency does not have to be caused by imbalance. An unbalanced rotating part develops centrifugal force, which causes it to vibrate at rotational frequency. Vibration at rotational frequency can also result from other conditions such as a bent shaft, an eccentric sheave, misalignment, and resonance. If vibration amplitude exceeds allowable tolerance at rotational frequency, the following steps should be taken before performing field balancing of rotating parts:

1. Check vibration amplitude as equipment goes up to operating speed and as it coasts to a stop. Any significant peaks at or near operating speed, as shown in Figure 16, indicate probable resonance (i.e., some part having a natural frequency close to the operating speed, resulting in greatly amplified levels of vibration).

    A bent shaft or eccentricity usually causes imbalance that results in significantly higher vibration amplitude at lower speeds, as shown in Figure 17, whereas vibration caused by imbalance generally increases as speed increases.

    If a bent shaft or eccentricity is suspected, check the dial indicator. A bent shaft or eccentricity between bearings as shown in Figure 18A can usually be compensated for by field balancing, although some axial vibration might remain. Field balancing cannot correct vibration caused by a bent shaft on direct-connected equipment, on belt-driven equipment where the shaft is bent at the location of sheave, or if the sheave is eccentric (Figure 18B). This is because the center-to-center distance of the sheaves fluctuates, each revolution resulting in vibration.

2. For belt- or gear-driven equipment where vibration is at motor driving frequency rather than driven speed, it is best to disconnect the drive to perform tests. If the vibration amplitude of the motor operating by itself does not exceed specified or allowable values, excessive vibration (when the drive is connected) is probably a function of bent shaft, misalignment, eccentricity, resonance, or loose holddown bolts.

3. Vibration caused by imbalance can be corrected in the field by firms specializing in this service or by testing personnel if they have appropriate equipment and experience.

Vibration at Other than Rotational Frequency. Vibration at frequencies other than driving and driven speeds is generally considered unacceptable. Table 4 shows some common conditions that can cause vibration at other than rotational frequency.

Resonance. If resonance is suspected, determine which part of the system is in resonance.

Isolation Mounts. The natural frequency of the most commonly used spring mounts is a function of spring deflection, as shown in Figure 19, and it is relatively easy to calculate by determining the difference between the free and operating height of the mount, as

Table 4 Common Causes of Vibration Other than Unbalance at Rotation Frequency

Frequency	Source
0.5 × rpm	Vibration at approximately 0.5 rpm can result from improperly loaded sleeve bearings. This vibration will usually disappear suddenly as equipment coasts down from operating speed.
2 × rpm	Equipment is not tightly secured or bolted down.
2 × rpm	Misalignment of couplings or shafts usually results in vibration at twice rotational frequency and generally a relatively high axial vibration.
Many × rpm	Defective antifriction (ball, roller) bearings usually result in low-amplitude, high-frequency, erratic vibration. Because defective bearings usually produce noise rather than any significantly measurable vibration, it is best to check all bearings with a listening device.

Amplitude peaks and then reduces as equipment reaches operating speed

Equipment operating just above resonance

Amplitude sharply increases just before or as equipment reaches operating speed

Equipment operating at or slightly below resonance
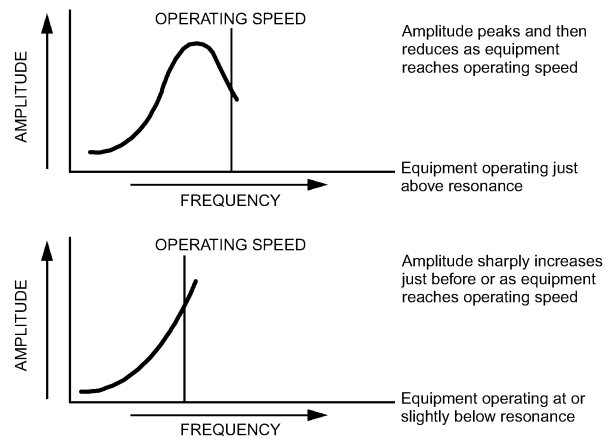
Fig. 16 Vibration from Resonant Condition
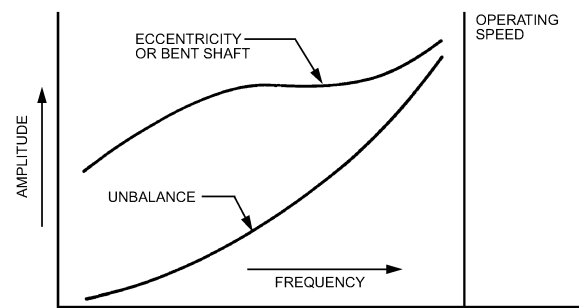
Fig. 17 Vibration Caused by Eccentricity
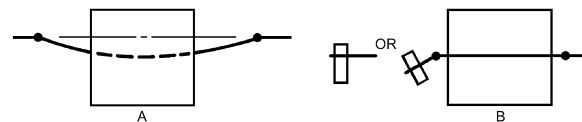
Fig. 18 Bent Shafts

$$f_n = \frac{1}{2\pi}\sqrt{g/\delta_{st}} = 3.13\sqrt{1/\delta_{st}}$$
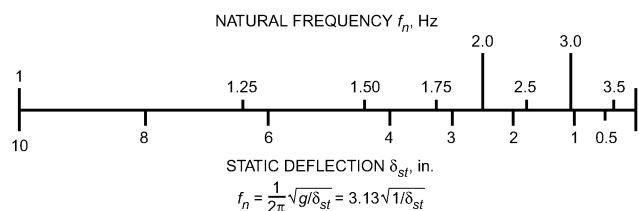
Fig. 19 Natural Frequency of Vibration Isolators

explained in the section on Testing Vibration Isolation. This technique cannot be applied to rubber, pad, or fiberglass mounts, which have a natural frequency in the 300 to 3000 cpm (5 to 50 Hz) range. Natural frequency for such mounts is determined by a bump test. Any resonance with isolators should be immediately corrected because it results in excessive movement of equipment and more transmission to the building structure than if equipment were attached solidly to the building (installed without isolators).

Components. Resonance can occur with any shaft, structural base, casing, and connected piping. The easiest way to determine natural frequency is to perform a bump test with a vibration spectrum analyzer. This test consists of bumping the part and measuring; the part will vibrate at its natural frequency, which will show up as a response peak on the analyzer. However, most of these instruments are restricted to frequencies above 500 cpm (8.3 Hz). They therefore cannot be used to determine natural frequencies of most isolation systems, which usually have natural frequencies lower than 500 cpm (8.3 Hz).

Checking for Vibration Transmission. The source of vibration transmission can be checked by determining frequency with a vibration analyzer and tracing back to equipment operating at this speed. However, the easiest and usually best method (even if test equipment is being used) is to shut off components one at a time until the source of transmission is located. Most transmission problems cause disturbing noise; listening is the most practical approach to determine a noise source because the ear is usually better than instruments at distinguishing small differences and changes in character and amount of noise. Where disturbing transmission consists solely of vibration, an instrument will probably be helpful, unless vibration is significantly above the sensory level of perception. Vibration below sensory perception is generally not objectionable.

If equipment is located near the affected area, check isolation mounts and equipment vibration. If vibration is not being transmitted through the base, or if the area is remote from equipment, the probable cause is transmission through connected piping and/or ducts. Ducts can usually be isolated by isolation hangers. However, transmission through connected piping is very common and presents many problems that should be understood before attempting to correct them (see the following section).

Vibration and Noise Transmission in Piping. Vibration and noise in connected piping can be generated by either equipment (e.g., pump or compressor) or flow (velocity). Mechanical vibration from equipment can be transmitted through the walls of pipes or by a water column. Flexible pipe connectors, which provide system flexibility to permit isolators to function properly and protect equipment from stress caused by misalignment and thermal expansion, can be useful in attentuating mechanical vibration transmitted through a pipe wall. However, they rarely suppress flow vibration and noise and only slightly attenuate mechanical vibration as transmitted through a water column.

Tie rods are often used with flexible rubber hose and rubber expansion joints (Figure 20). Although they accommodate thermal movements, they hinder vibration and noise isolation. This is because pressure in the system causes the hose or joint to expand until resilient washers under tie rods are virtually rigid. To isolate noise adequately with a flexible rubber connector, tie rods and anchor piping should not be used. However, this technique generally cannot be used with pumps on spring mounts, which would still permit the hose to elongate. Flex-

ible metal hose can be used with spring-isolated pumps because wire braid serves as tie rods; metal hose controls vibration but not noise.
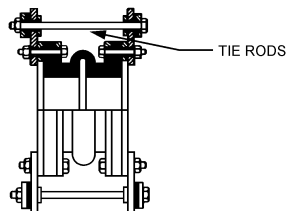
Problems of transmission through connected piping are best resolved by changes in the system to reduce noise (improve flow characteristics, reduce impeller size) or by completely isolating piping from the building structure. Note, however, that it is almost impossible to isolate piping completely from the structure, because the required resiliency is inconsistent with rigidity requirements of pipe anchors and guides. Chapter 47 contains information on flexible pipe connectors and resilient pipe supports, anchors, and guides, which should help resolve any piping noise transmission problems.

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Fig. 20   Typical Tie Rod Assembly

CHAPTER 38

OPERATION AND MAINTENANCE MANAGEMENT

ALTHOUGH facilities maintenance was once the responsibility of trained technical personnel, increasingly sophisticated systems and equipment require overall management programs to handle organization, staffing, planning, and control. These programs should meet present and future occupant, facility personnel, and technical requirements. They should also meet system availability, energy use, and environmental requirements; enhance management and operator skills; and increase communication among stakeholders (e.g., owners, maintenance planners, maintenance technicians, contractors, occupants) of cost-effective operation and maintenance.

Good maintenance management planning includes proper cost analysis and a process to ensure that occupant comfort, energy planning, and safety and security systems are optimal for all facilities. Appropriate technical expertise, whether in-house or contracted, is also important. This chapter addresses the following issues:

- Cost-effectiveness
- Management approaches according to criticality of buildings or systems
- Documentation and record keeping
- Condition monitoring and maintenance
- Operation and maintenance responsibilities of designers, contractors, manufacturers/suppliers, and owners

Operation, maintenance, and maintainability of all HVAC&R systems should be considered during building design. Any successful operation and maintenance program must include proper documentation of design intent and criteria. ASHRAE *Guideline* 4 provides a methodology to properly document HVAC systems. Newly installed systems should be commissioned according to the methods and procedures in ASHRAE *Guideline* 1 to ensure that they are functioning as designed. It is then the responsibility of management and operational staff to maintain design functionality throughout the life of the building. Existing systems may need to be reconfigured and recommissioned to accommodate changes. (See Chapter 42 for additional information on commissioning.)

TERMINOLOGY

Condition-based maintenance uses manual and automated inspection and monitoring to establish the current condition of equipment. It also uses condition and performance indices to optimize repair intervals.

Corrective maintenance classifies resources, expended or reserved, for predicting and correcting conditions of impending failure. Corrective action is strictly remedial and always performed before failure occurs. An identical procedure performed in response to failure is classified as a repair. Corrective action may be taken during a shutdown caused by failure, if the action is optional and unrelated.

Durability is the average expected service life of a system or facility. Table 3 in Chapter 36 lists median years of service life of various equipment. Individual manufacturers quantify durability as design life, which is the average number of hours of operation before failure, extrapolated from accelerated life tests and from stressing critical components to economic destruction.

Failure is the inability of a system or equipment to perform its intended function at an acceptable level.

Fault detection and diagnosis is a systematic procedure to compare measured and expected system performance and determine the cause of discrepancies.

The **maintenance program** defines maintenance in terms of scope, procedures, frequency, and resource allocation. It documents objectives, establishes evaluation criteria, and commits the maintenance department to basic areas of performance, such as prompt response to mechanical failure and attention to planned functions that protect capital investment and minimize downtime and failures.

Planned maintenance classifies resources invested in selected functions at specified intervals. All functions and resources within this classification must be planned, budgeted, and scheduled. Planned maintenance includes preventive and corrective maintenance.

Predictive maintenance is a function of corrective maintenance. Statistically supported objective judgment is implied. Nondestructive testing, chemical analysis, vibration and noise monitoring, and routine visual inspection and logging are classified under this function, provided that the item tested or inspected is part of the planned maintenance program.

Preventive maintenance classifies resources allotted to ensure proper operation of a system or equipment under the maintenance program. Durability, reliability, efficiency, and safety are the principal objectives.

To **repair** is to restore to good condition with the following constraints: (1) operation is fully restored without embellishment, and (2) failure triggers the response.

Results-oriented maintenance provides the required reliability and availability at the lowest cost by identifying and implementing actions that reduce the probability of failure.

Run to failure is a strategy applied when the cost of maintenance or repair may exceed the cost of replacement or losses in the event of failure. Only minimum maintenance such as cleaning or filter change is performed. The equipment may or may not be monitored for proper operation, depending on the consequences of failure. For example, a window air conditioner may be run although it is vibrating and making noise, then replaced rather than repaired.

System effectiveness is a system's ability to perform its intended function.

System operation defines (1) the parameters that the building or systems operator can adjust to satisfy occupant comfort or process

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The preparation of this chapter is assigned to TC 7.3, Operation and Maintenance Management. Significant content on fault detection and diagnostics was provided by TC 7.5, Smart Building Systems.

requirements and (2) the strategy for optimum energy use and minimum maintenance.

Unplanned maintenance classifies resources expended or reserved to handle interruptions in the operation or function of systems or equipment covered by the maintenance program. This classification is defined by a repair response.

RESULTS-ORIENTED MAINTENANCE MANAGEMENT

Results-oriented maintenance management provides maintenance with the required reliability and availability at the lowest cost. This strategy involves identifying and implementing actions that cost-effectively reduce the probability of failure. In general, investments are made in maintenance to promote longevity of mission-critical assets to help the organization succeed over the long term.

It is useful to compare maintenance costs to the total costs of facility ownership. The major categories of the life-cycle cost of facility ownership are (1) design and construction, (2) operations and maintenance, and (3) acquisition, renewal, and disposal.

Representative life-cycle costs can be distributed as shown in Figure 1. Over the expected life of a typical facility, owners need to apportion funds to cover these basic segments.

It is important to compare the relative significance of these categories over an expected life cycle. Studies of the federal sector (Christian and Pandeya 1997) illustrate the relative amounts of financial resources (in some cases, as much as 85% of total life-cycle costs) required to sustain each phase of facility ownership. The results of these studies are shown in Figure 2. Over a nominal 30 yr term, operation and maintenance (O&M) comprise the largest segment of facility ownership cost. The intent of results-oriented maintenance management is to minimize operation and maintenance costs through proactive efforts in all three segments.

Prudent facility ownership should invest appropriately in acquisition, design, and construction considering future O&M expenses. Low first cost for capital projects or replacement of obsolete equipment must be weighed against the long-term effect of potentially more frequent and/or more time-consuming maintenance and repair, resulting in higher operating costs. In addition, maintenance management should consider an optimum mix of techniques to minimize maintenance costs and mitigate risk of failure. Facility design and maintenance approach decisions should consider their long-term effects on maintenance and operations costs for maximum financial benefit.
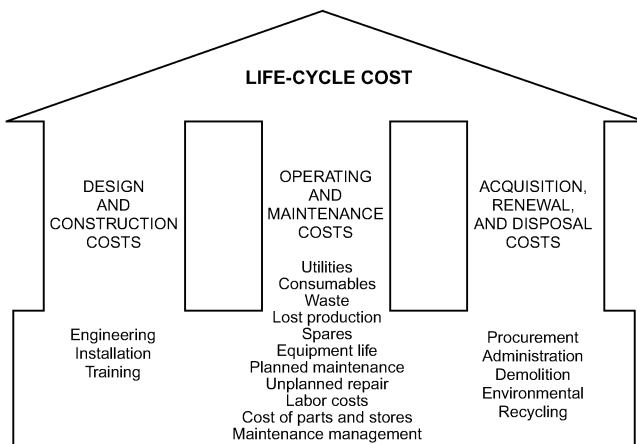
Concepts

Identifying the major concepts of results-oriented facility operation and maintenance clarifies how the various elements are interrelated and, when managed effectively, how they contribute to the bottom line. The major concepts include the following:

- **Availability** is the amount of time that machinery or equipment is operable when needed. Often referred to as *uptime*, availability improvements translate to increased production for manufacturing and industrial companies. Availability is often confused with reliability, which can be seen as a component of availability.
- **Capability** is a system's ability to satisfactorily provide required service. It is the probability of meeting functional requirements when operating under a designated set of conditions. An example of capability is the ability of a heating system to cope with the heating load at design winter temperature. Capability must be verified when the system is first commissioned and whenever functional requirements change.
- **Deliverability** is the total amount of production delivered to users per unit of time. High deliverability is clearly supported by high levels of the other concepts.
- **Dependability** is the measure of a system's condition. Assuming the system was operative at the beginning of its service life, dependability is the probability of its operating at any other given time until the end of its life. For systems that cannot be repaired during use, dependability is the probability that there will be no failure during use. For systems that can be repaired, dependability is governed by how easily and quickly repairs can be made.
- **Maintainability** is the ease, accuracy, safety, and economy of maintenance. This concept is an important design characteristic. The purpose of maintainability is to improve the effectiveness and efficiency of maintenance.

  For some industries, maintainability is quantitative, corresponding to the probability of performing a maintenance action or repair in specified period of time using prescribed procedures in a specified environment. For others, maintainability is simply the ease with which maintenance actions can be performed.
- **Operability** is the efficient conversion of labor, raw materials, and energy into product, in which the ratio of output to input is optimal. Maintainability and reliability contribute to availability. High levels of availability minimize the input required for a given output, thereby contributing to high levels of operability.
- **Reliability** is the probability that a system or facility will perform its intended function for a specified period of time when used under specific conditions and environment. Issues affecting reliability include operating practices, equipment and system design, installation, and maintenance practices.

Fig. 1   Three Pillars of Typical Life-Cycle Cost with Cost Elements
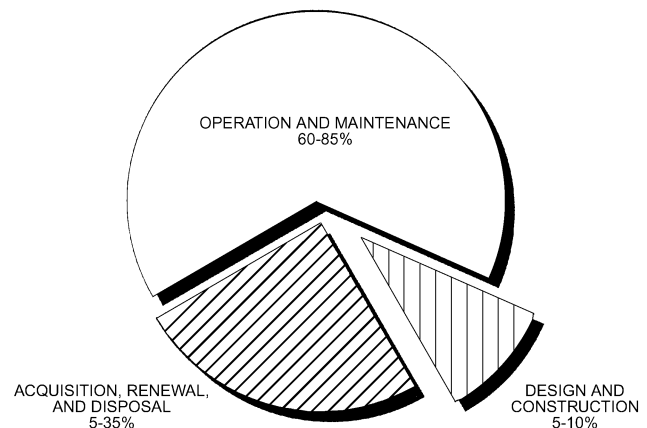
Fig. 2   Life-Cycle Cost Elements: 30-Year Period for Federal Facilities

- **Sustainability** is "providing for the needs of the present without detracting from the ability to fulfill the needs of the future" (ASHRAE 2006). Sustainable maintenance management includes identifying and reducing a building's detrimental environmental effects during its operating lifetime. Sustainability in buildings cannot be achieved simply through sustainable design practices, but also requires sustainable operation and maintenance.
- **System effectiveness** is a system's ability to perform its intended function in terms of performance, availability, and dependability. Ideally, a facility must provide the required level of services satisfactorily and must operate dependably without failure for the given period.

Concept Interrelationships

Results-oriented maintenance management concepts are closely related and interdependent. There are multiple perspectives of the interrelationship among maintainability, reliability, and availability. Maintainability and reliability are often grouped together, because they deal with essentially the same design concepts from different perspectives. Reliability analyses often serve as input to maintainability analyses. Here, maintainability and reliability are considered independent concepts, both of which contribute to availability. Increased availability, along with operability, can significantly improve profitability. Figure 3 shows these relationships: reliability and maintainability combine to yield availability, which then combines with operability to yield deliverability. Because these concepts are interrelated, improvements in any area (all else being equal) ultimately lead to improved results, or profitability.

Results-oriented maintenance management is effective at integrating proactive maintenance effectiveness and efficiency into the total cost of facility ownership. If adequate measures for cost-effective maintainability are not integrated into the design and construction phases of a project, reliability and/or uptime are likely to be adversely affected and total life-cycle costs probably increase significantly. Appropriate levels of maintainability seldom occur by chance. They require up-front planning, setting objectives, disciplined design implementation, and feedback from prior projects. It is vital to identify critical maintainability and production reliability issues and integrate them into facility project designs to achieve long-term facility owning and operating benefits.

Each concept has a sustainability element. For example, good reliability and availability may minimize or eliminate the need for installed spare capacity, thereby reducing the facility's footprint and use of resources. Good operability increases efficiency and reduces energy use. Sustainability is clearly an overriding benefit of effective, results-oriented maintenance management.

DOCUMENTATION

Operation and maintenance documentation should be prepared as outlined in ASHRAE *Guideline* 4. Information should be documented as soon as it becomes available. This supports design and construction activities, systems commissioning, and training of operation and maintenance staff.

A complete operation and maintenance documentation package consists of the following documents:

SUSTAINABILITY

RELIABILITY (FUNCTION) → AVAILABILITY (UPTIME) → DELIVERABILITY (OUTPUT) → IMPROVED RESULTS (PROFITABILITY)

MAINTAINABILITY (TIME)

OPERABILITY (EFFICIENCY)

Fig. 3   General Interrelationship of Concepts

- The **operation and maintenance document directory** should provide easy access and be well organized and clearly identified.
- **Emergency information** should be distributed to emergency personnel and be immediately available during emergencies; it should include emergency and staff and/or agency notification procedures.
- **The operating manual** should contain the following information:

  I. General information

     A. Building function
     B. Basis of design
     C. Building description
     D. Operating standards and logs

  II. Technical information

     A. System description
     B. Operating routines and procedures
     C. Seasonal start-up and shutdown
     D. Special procedures
     E. Basic troubleshooting

- **The maintenance manual** should contain the following information:

  I. Equipment data sheets (specific to installed equipment)
     A. Operating and nameplate data
     B. Warranty

  II. Maintenance program information
     A. Manufacturer's installation, operation, and maintenance instructions
     B. Spare parts information
     C. Preventive maintenance actions
     D. Schedule of actions
     E. Action descriptions
     F. History

- **Test reports** document observed performance during start-up and commissioning and should be compiled throughout the service life of the facility.
- Copies of **construction documents** should be included.

These documents should be available to the entire facilities department.

MAINTENANCE MANAGEMENT

Maintenance management is the planning, implementation, and review of maintenance activities. Myriad levels of maintenance management, ideally determined by cost-effectiveness and by health and safety concerns, can be established. Cost-effectiveness is the balance between system effectiveness (e.g., maintenance levels, equipment and system availability, reliability, maintainability, and performance) and life-cycle costs.

There are three main maintenance strategies. In **run-to-failure**, minimal resources are invested in maintenance until equipment or systems break down (i.e., fail). **Preventive maintenance** is scheduled, either by run time or by the calendar. **Condition-based maintenance** is based on equipment monitoring to establish the current condition of equipment and on condition and performance indices to optimize repair intervals. *Predictive maintenance*, a type of condition-based maintenance, goes one step further, using predictions of future equipment condition to optimize maintenance actions. Within each group, the level of effort can vary from cursory to extensive. Maintenance programs may incorporate features of all these approaches into a single program. Many arguments can be made about the cost-effectiveness of each of these programs.

Operation and maintenance costs represent a significant portion of a facility's total life-cycle cost (see Figure 2). Therefore, the cost-effectiveness of maintenance management is paramount.
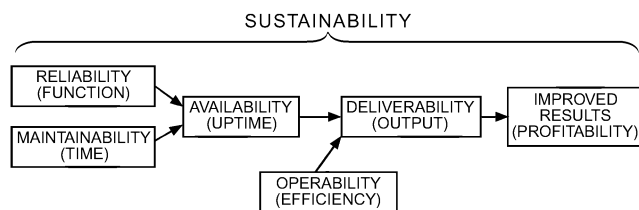
Proper operation and maintenance are important factors in providing good indoor air quality (IAQ) and ensuring that life safety systems operate as designed.

The success of maintenance management depends on dedicated, trained, and accountable personnel; clearly defined goals and objectives; measurable benefits; management support; and constant examination and reexamination.

KNOWLEDGE AND SKILLS

To be effective and efficient, operation and maintenance programs require staff with the right combination of technical and managerial skills. Technical skills range from hands-on correct application of methods and procedures to the analytical problem-solving expertise of the physical plant engineer.

Physical plant engineers require a variety of skills to effectively operate HVAC systems selected by the designer, implement the maintenance program, manage operating and maintenance staff, and meet requirements of the investment plan. Good physical plant engineering solutions are developed while the investment plan is being formulated, and continue throughout the life of the facility.

Managerial skills include overseeing the stewardship of the facility in life-cycle terms and on a day-to-day basis. Management at this level may develop maintenance strategy; determine program goals and objectives; and administer contracts with tenants, service providers, and labor unions. Specialized contractual maintenance companies require the manager to have a basis understanding of the specialty to define the required work and to determine whether the requirement has been met.

LEVELS OF EFFORT

The criticality and complexity of the system to be operated and maintained must be considered when developing the maintenance strategy. Building complexity and criticality range from residential, commercial, institutional, and industrial, to mission-critical facilities (e.g., cleanrooms, operating rooms). The maintenance strategy and resultant maintenance program must account for system complexity and criticality so that the desired uptime results are achieved.

The foundation of an effective maintenance program is obtaining good baseline data, which commissioning can provide. All installed systems, no matter how simple, should have a commissioning plan; this gives the building or system owner and users a means of operating the system in the most economical manner, minimizing energy consumption and maintenance costs while meeting user requirements. The following sections provide example levels of effort for maintaining three expected types of systems.

Basic Systems

Basic systems may include mechanical equipment such as a rooftop unit with an air handler, refrigeration compressor, and condensing system in a single package. Many of these systems have simple operating procedures, such as switching a single-zone thermostat from heating to cooling to control temperature for building occupants. Maintenance procedures for this type of system are usually limited to those recommended by most manufacturers or lessons learned through operating experience with the system.

In most situations, an onsite maintenance staff changes filters, belts, and motors, and lubricates bearings. However, tasks such as cleaning condenser and evaporator coils and assessing refrigeration and control systems may require a more specialized technician. This also applies to heating components such as gas or oil burners and electric elements. Tasks that may have previously been done by the onsite maintenance staff may now require certification and special equipment [e.g., U.S. Environmental Protection Agency (EPA) certification of technicians and recovery units for refrigeration handling]. In most small facilities, maintenance contractors provide this

service. The frequency of maintenance depends in part on system run time and type of operation in the facility.

Smaller facilities may also have more complex control systems, especially when zoning is critical for a variety of load conditions. Whenever the operator cannot service and repair the systems or components installed, the owner should ensure that qualified contractors and technicians perform the work.

Dirty evaporator and condenser coils and filters require additional energy to operate, because inefficient heat transfer creates higher compressor discharge pressures, so more energy is required for a given load. The system must also operate longer to satisfy space conditions. Although these items are variable and difficult to quantify, proper maintenance improves system operation and equipment life, regardless of system size.

Medium-Complexity Systems

The next level of systems uses several pieces of mechanical equipment acting together through a control system to provide a variety of comfort zones.

Commissioning and training are increasingly important with these types of systems to ensure optimum comfort at minimal energy cost. Without detailed commissioning documentation, operation staff cannot effectively consider factors such as energy budgets when addressing building occupants' comfort complaints.

To manage maintenance in medium-sized facilities, programs must be developed for maintenance personnel. Maintenance programs should define which equipment is included, what tasks are to be done, and when the tasks are to be performed. The goal of the maintenance program is to reduce the risk and impact of equipment failure. Over time, maintenance programs can be adjusted for the system's particular characteristics. Computerized maintenance management systems (CMMS) can help management track program progress and report results.

Medium-sized systems can have many levels of specialization and separation of operation and maintenance functions. Operation and maintenance (O&M) personnel may be employed by the building owner or user. These personnel should have the general technical knowledge to operate and maintain these systems in accordance with operational and performance goals determined by management. It is beneficial for O&M staff to have experience or knowledge about commissioning in case they did not participate in the original facility commissioning process.

Initial system maintenance procedures should be detailed in the maintenance manual (with individual equipment maintenance frequency detailed in manufacturers' literature) that was furnished during the initial installation or developed after installation. The maintenance program should be tailored to each specific facility and system type. The maintenance program may evolve based on experience, introduction of new technology, or expiration of equipment warranty requirements. It may be necessary to contract out certain maintenance program functions for complex equipment, if staff do not have adequate technical expertise.

Complex Systems

Systems containing more than several pieces of mechanical equipment, including those with central plants, are considered to be complex. Some of these facilities, including those with central plants, require management to hire, direct, and oversee two staffs: one of operation personnel, and the other of maintenance personnel.

The operations budget should be appropriate to support computerized maintenance programs, which detail proper timing of system maintenance procedures so that all systems operate at maximum efficiency while maintaining occupant comfort. Annual and life-

cycle cost planning are essential to ensure the most cost-effective operation and maintenance of these systems.

If the building is being commissioned, O&M management should be involved with the predesign, design, and construction phases of the facility. Because facilities are long-term investments, any first-cost compromises must consider both life-cycle cost and ability to satisfy occupant comfort while maintaining reasonable energy budgets.

Logged operating information can be used with proper database management systems as a predictive maintenance tool by monitoring the rate of condition and performance degradation before the equipment actually fails. This tool may be used to indicate equipment needing attention so that management can make appropriate decisions or changes. Like basic and medium-complexity systems, complex systems may require an outsourced contractor or manufacturer's technical support for specific equipment.

CONDITION MONITORING AND ASSESSMENT

An important aspect of operation and maintenance engineering systems is assessing equipment condition. For complex systems, it may be necessary to monitor several conditions (e.g., temperature, vibration, and load) so that the overall condition can be assessed.

One of the most effective condition-monitoring practices is the routine operating plant inspection conducted by the technician during regularly scheduled plant tours. A technician's knowledge, experience, and familiarity with the plant are invaluable tools in plant diagnostics. Plant familiarity, however, is lost with frequent technician staff changes.

Many physical parameters or conditions can be measured objectively using both special equipment and conventional building management system sensors. One such condition is vibration on rolling element bearings. Vibration data are captured by computers, and special software can analyze the data to determine whether shaft alignment is correct, whether there are excessively unbalanced forces in the rotating mass, the state of lubrication of the bearing, and/or faults with the fixed or moving bearing surfaces or rolling elements. Not only can this technique diagnose failures and repair requirements at an early stage, but it can also be used after completing a repair to ensure that the underlying cause of failure has been removed.

Other condition-monitoring techniques include (1) using thermal infrared images of electrical connections to determine whether mechanical joints are tight, (2) analyzing oil and grease for contamination (e.g., water in fuel oil on diesel engines), (3) analyzing electrical current to diagnose motor winding faults, (4) measuring differential pressure across filter banks and heat exchangers to determine optimum change/cleaning frequency, and (5) measuring temperature differences for correct control valve response or chiller operation.

In some cases, multiple parameters are required. For example, to determine the degree of contamination of an air filter bank on a variable-air-volume (VAV) system, it is necessary to measure the differential pressure across the filter and interpret it in terms of the actual flow rate through the filter. This can be done either by forcing the fan on to high speed and then measuring the differential pressure, or by combining a flow rate signal with a differential pressure signal.

Timely detection of equipment faults can reduce energy consumption and operating costs. Surveys and site measurements have documented a wide variety of operating faults in common HVAC equipment.

FAULT FREQUENCY AND COSTS

Air Conditioners

Breuker and Braun (1998) and Breuker et al. (2000) compiled fault data for air conditioners from a database of more than 6,000 "no air-conditioning" fault cases between 1989 and 1995. Frequencies of

Table 1 Normalized Frequency of Occurrence and Repair Costs for Air Conditioners

Cause	% of Total	
	Frequency[a]	Cost[b]
Controls error	21	10
Electrical problem	20	7
Refrigerant leak	12	5
Condenser	7	9
Air handling	7	5
Evaporator	6	6
Compressor	5	24
Cooling water loop	4	4
New installation	—	10
Other	18	20

[a]In-service equipment only   [b]New and in-service equipment

Table 2 Normalized Frequency of Occurrence and Repair Costs for Chillers

Cause	% of Total*					
	Centrifugal Compressor		Screw Compressor			
			Water-Cooled		Air-Cooled	
	Frequency	Cost	Frequency	Cost	Frequency	Cost
Control box/ starter	33	18	30	23	39	22
System-level fault	23	21	28	28	27	27
Condenser	17	8	5	4	10	12
Compressor	11	46	5	29	6	23
Lubrication	7	5	15	7	—	—
Piping	7	2	16	8	10	4
Evaporator	2	1	2	1	8	12

*Normalized costs may not sum to 100 because of rounding.

fault occurrence and repair costs were estimated from a statistically representative sample of the data and are presented in Table 1.

Other studies also identify significant maintenance problems. A California Energy Commission project (Jacobs et al. 2003) studied 215 rooftop units in 75 buildings and found that 63% of the economizers were malfunctioning, 46% had incorrect refrigerant charge, and 39% had low airflow. Additionally, there were numerous controls-related problems. Diagnostic test results from over 55,000 air-conditioning units (Proctor 2004) showed that over 95% of residential units failed the test because of duct leakage; airflow restriction; deficient insulation, refrigerant charge, or evaporator airflow; oversized units; or noncondensables in the refrigerant. Charge was incorrect in 62% of the residential units and 60% of the commercial units, and recommended charging methods were not used 74% of the time. Evaporator airflow was low in 63% of commercial units. Rossi (2004) analyzed data collected by technicians servicing 1468 cooling stages in residential and commercial unitary equipment. Fifty-eight percent of the stages required tune-ups and 10% required major maintenance to remove refrigerant-line restrictions or replace compressors. Of the units requiring tune-up, 63% needed refrigerant charge, 22% had dirty evaporator coils, 10% had dirty condenser coils, 4% were overcharged, and 1% had evaporator fans running too fast.

Chillers

Four manufacturers provided 170 service records for centrifugal chillers, 228 service records for water-cooled screw chillers, and 111 service records for air-cooled screw chillers (Comstock et al. 2002). Results are shown in Table 2. The most common faults were (1) in the control box and starter, and (2) refrigerant leakage, a system-level fault. Infrequent compressor-motor burnouts are the most expensive.

Screw chillers show fewer problems with bearing failure than chillers with centrifugal compressors, but have more problems with piping systems. Repair costs for motor burnout in air-cooled screw compressors are lower than for other compressor types. Refrigerant leakage was slightly more common for air-cooled than for water-cooled chillers, but the relative repair costs were lower; smaller air-cooled screw chillers use less refrigerant, and thus have lower refrigerant replacement costs.

Air-Handling Systems

Faults in air-handling units (AHUs) have been reported from limited field tests of methods to automatically detect and diagnose these faults (House et al. 2003). House et al. (2001) tested a rule-based fault detection and diagnosis (FDD) method in five AHUs in a single building over 15 weeks. Faults were found in 52% of the occupied hours; faults included excessive mode switching, failure to maintain supply air temperature at set point, excessive ventilation during heating mode, and prolonged manual override of automatic controls. Observed control problems were known to building operators and resulted in replacement of numerous damper motors.

Katipamula et al.'s (1999) method detects AHU outdoor air problems, such as too little outdoor air, which is a potential air quality problem; too much outdoor air, resulting in excessive heating or cooling; inappropriate operation of the economizer; and control problems such as mechanical cooling when the AHU is supplying 100% outdoor air and should satisfy the cooling load, bias in the outdoor air temperature sensor, or a stuck outdoor air damper. The system, which is based on rules developed from engineering models of air-handler performance and is implemented as a decision tree, was evaluated in 32 AHUs in seven test buildings and found problems in nearly all of the AHUs. Problems found included faulty sensors, mislocated sensors, stuck dampers, operation during unscheduled times, excess ventilation, and inadequate ventilation (Katipamula et al. 2003).

A set of performance indices was developed to detect zone temperature and airflow errors and excessive control action in VAV terminal boxes (Seem et al. 1999). Significant flow errors were found in two of 24 dual-duct VAV boxes in a field test; one box had a defective motor capacitor, and the other had an incorrectly installed damper actuator.

CONDITION-BASED MAINTENANCE

Condition-based maintenance involves carrying out maintenance only on the basis of the conditions monitored and the interpretation of those conditions. This should result in performing maintenance work only when necessary; therefore, plant reliability will be optimized, and personnel productivity will improve.

Many repairs are a direct result of maintenance-induced failures occurring during scheduled maintenance. Condition-based maintenance prevents unnecessary, repetitive work. There can, however, be added costs involved in supplementary training and instrumentation.

Conditions are monitored on an on/off basis and comparisons are made versus known values (e.g., tabulated values of acceptable vibration). Generally more useful in analysis of building systems is trending over a period of time: either measuring conditions at a regular interval so that a gradual deterioration can be tracked and remedial work planned in advance or, where deterioration can be rapid, continual monitoring.

In the case of air filters in a VAV system, assuming the fan draws air through the filter and is controlled to a fixed static pressure, the filter change criterion is a function of the maximum differential pressure the fully loaded filter can withstand without bursting and the energy consumption of the fan. It may be more economical to change the filter before the maximum pressure is reached if the rate of loading is slow. Monitoring with the energy management system rather than changing on a fixed time interval means that if some-

thing occurs to rapidly accelerate dust loading (e.g., nearby construction work), the system alerts building management before filters are overloaded and could potentially burst.

In a constant-volume system (again, assuming the main fan is drawing air through the filter), the change criterion is a function of the maximum differential pressure the filter can withstand and the drop in flow rate that can be tolerated by system users. As the filter becomes dirty, energy consumption decreases and filter efficiency improves. A fixed time interval for filter bank changing/cleaning is not optimum. Changing on the basis of a monitored condition should optimize filter life and minimize labor cost for building cleaning and this aspect of plant maintenance.

BENEFITS OF DETECTING AND DIAGNOSING EQUIPMENT FAULTS

An HVAC&R system tune-up pilot program in Wisconsin evaluated energy and demand savings at nine sites, including retail and grocery stores, restaurants, and an office building (Karmar and Valerie 1995). Energy savings of up to 15% were achieved in most buildings. A two-year study of rooftop heating and cooling equipment by the Electric Power Research Institute (Krill 1997) found significant changes in unit performance caused by low refrigerant charge (the most common problem), filter maintenance, or coil cleaning, and concluded that the cost of annual maintenance would likely exceed utility savings.

Rossi's (2004) fault survey of unitary equipment used measurements by service technicians to compute four performance indices, from which unit efficiency was estimated and savings potential calculated. Fifty percent of the equipment was estimated to have a savings potential of at least $170/year, and 33% had a potential of at least $225/year.

Automated detection and diagnosis of faults may reduce service costs as well as operating costs. Li and Braun (2004a) developed an economic evaluation procedure to estimate savings from 20 monitored field sites. The sites included small retail, play areas for fast-food restaurants, and modular classrooms, in coastal and inland California climates. Hardware and software costs for their FDD system were estimated at $250 to $600 for individual units, and $700 to $1500 for a site with four units. Payback periods were less than one year, with savings in operating costs and an estimated 70% reduction in service costs.

The automated FDD system used by Li and Braun predicts the values of six measured system temperatures as a function of load and environmental conditions: evaporator, superheat, condenser, liquid-line subcooling, and hot-gas temperatures in the refrigerant loop and air-side differences across the evaporator and condenser (Rossi and Braun 1997, modified by Li and Braun 2004b). Differences between measurement and prediction were used to detect and classify compressor-valve leakage; condenser fouling; evaporator fouling; liquid-line restriction; noncondensable gas; and refrigerant leakage, undercharge, and overcharge. In another system now in widespread use, service technicians provide equipment specifications and operating conditions, including evaporator inlet and outlet air temperatures and refrigerant temperatures and pressures, and receive an on-the-spot analysis of refrigerant charge and evaporator airflow relative to manufacturer's specifications (Downey and Proctor 2002).

RESPONSIBILITIES

For new construction or renovation, the building owner should work with the designer to clearly define facility requirements. In addition to meeting the owner's project requirements, the designer must provide a safe and efficient facility with adequate space to inspect and repair components. The designer must reach agreement with the owner on the criticality of each system to establish items such as access, redundancy, and component isolation requirements.

System design must include operation (e.g., temperature, humidity, cleanliness, air change rate, relative pressure), flow diagrams, instrumentation, and control sequences. The equipment supplier must provide equipment meeting the specifications, and should also recommend alternatives that offer lower life-cycle costs for the owner and designer to evaluate. The installing contractor must turn over the newly installed system to the owner in an organized and comprehensive manner, including complete documentation with O&M manuals and commissioning reports (e.g., air balance, fume hood certification).

An effective director should be able to organize, staff, train, plan, and control the operation and maintenance of a facility with the cooperation of senior management and all departments. A manager's responsibilities include administering the operation and maintenance budget and protecting the life-cycle objectives. Before selecting a least-cost alternative, a manager should determine its effects on durability and loss prevention (Loveley 1973).

CONVERSION TO NEW TECHNOLOGY

Operation and maintenance programs are based on the technology available at the time of their preparation. The programs should be adhered to throughout the required service life of the facility or system. During the service life, new technology (e.g., automated detection and diagnosis of operating faults) may become available that would affect the operation and/or maintenance program. Conversion from existing to new technology must be assessed in life-cycle terms. The existing technology must be assessed for the degree of loss from shorter return on investment. The new technology must be assessed for (1) all initial, operation, and maintenance costs; (2) the correlation between its service life and the remaining service life of the facility; and (3) the cost of conversion, including revenue losses from associated downtime.

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CHAPTER 39

COMPUTER APPLICATIONS

COMPUTERS are used in a wide variety of applications in the HVAC industry. Rapid technological advances and the decreasing cost of computing power, memory, and secondary storage have changed many aspects of the HVAC industry. New HVAC design tools allow optimal solutions to be found in engineering applications. Building operations benefit from low-cost networking to achieve multivendor control system interoperability. Consulting engineers can search manufacturers' equipment and specifications interactively over the Internet. Designers can collaborate from remote locations. More powerful applications that are also easier to use are now affordable by a wider segment of the industry; many HVAC calculations, such as heating and cooling loads, can be performed easily and automatically.

Business applications and infrastructure have also positively affected the HVAC industry. Open communications standards and internetworking allow fast, efficient communications throughout company and industry circles. HVAC design, manufacture, installation, and maintenance functions benefit as businesses build computing infrastructure through corporate information services (IS) or information technology (IT). Many advances in the business community have been adopted by the HVAC industry as de facto standards.

COMPUTER SYSTEM COMPONENTS AND TECHNOLOGIES

Because of rapid advances in computer technology, computers offer tremendous power at very low cost. However, the total cost of ownership of a personal computer is not limited to the cost of the computer hardware. Software, network connectivity, support, and maintenance expenses quickly surpass the initial cost of hardware.

Selecting a computer platform includes a wide variety of issues, such as

- Analysis of application needs
- Corporate computer support architecture and standards
- Vendor support, including guaranteed response time
- Central processing unit (CPU) power, random-access memory (RAM), and secondary or hard disk storage capacity
- System compatibility and interoperability between vendors
- Ease of use and required training
- Data backup strategy: how will the data on the computer be restored in the event of a system failure?
- Security issues: what data will be accessible, and how will data be protected from unauthorized access?
- Network communications capability and compatibility
- Technical support live and/or online, including driver update support
- Web site support
- Software driver update support/reliability

The preparation of this chapter is assigned to TC 1.5, Computer Applications.

- Cost/benefits comparison
- Information system infrastructure/interoperability requirements
- Technology reliability and obsolescence
- Total cost of ownership

Virtually all brand-name personal computers now have more than enough speed for basic business applications such as word processing and spreadsheets. Personal computers differ in their ability to handle multimedia graphics and sound, which are useful in advanced software applications.

An information system comprised of computer networks depends on the ability of computers to communicate with each other in a standard architecture. Technological advances have resulted in computer systems becoming obsolete in less than five years. Therefore, it is important to plan for compatibility with future business computer requirements. Software and hardware must match the needs of the user, and be consistent with the business system architecture.

System architecture standards from organizations such as the Institute of Electrical and Electronics Engineers (IEEE), the American National Standards Institute (ANSI), and the International Organization for Standardization (ISO) have resulted in well-defined standards such as Ethernet, TCP/IP, and HTTP, further described in the section on Networking Components. The combination of popular standards has resulted in network and Internet accessibility from local computers.

COMPUTER HARDWARE

Hardware is the physical equipment (electronic parts, cables, printed circuit boards, etc.) that provides the foundation for the software to run. Hardware processing power has increased dramatically, such that the average business system provides much more capacity than the average user needs. Specialized tasks, however, often require specialized hardware.

Mainframes are large, expensive computer systems that serve the majority of large-scale business and technical needs. Mainframe computers best serve large nationwide databases, weather prediction, and scientific modeling applications. They support many users simultaneously, and are usually accessed over a network from a personal computer (PC). More powerful mainframes are called **supercomputers**.

Personal computers (PCs) are desktop computers tailored to individual user needs, and provide much more convenient access to computing resources than the traditional mainframe. PCs are used in a wide variety of information-gathering, communication, organization, computation, and scheduling roles.

PC servers allow access to files and data on a network. PC servers are a special class of computers that support large amounts of memory, fast connection speed to the network, large disk storage for access of many files, and applications designed to be usable from other computer systems. Because system reliability is critical, there are additional features such as better construction, component redundancy, and removable hard drives.

Workstations are application-specific computers serving specialized needs such as computer-aided design (CAD) and manufacturing (CAM), product design and simulation, mapping geographic information system (GIS), or specialized graphics design. Workstations have greater processing power and graphical display capabilities than personal computers, and may also have other improvements found in PC servers.

Clusters are several PCs or workstations organized to work together. Clusters of PCs can approach the computing power of a mainframe at a fraction of the cost, if efficient application software is available. Clusters of workstations can provide more computing power than even the largest mainframe.

Minicomputers are medium-sized business computer systems that serve medium to large application needs. Minicomputers have been used to economically scale applications that have grown too large for PC servers. Many small business e-commerce applications have moved to the minicomputer platform.

A **Web server** is a PC server, minicomputer, or mainframe that stores and distributes Web-based information; it is typically used to distribute documents and other information across the Internet.

Laptop computers are smaller, battery-powered personal computers optimized for light weight and portability. Compared to a similarly priced personal computer, laptops are generally slower and have fewer features, though they generally include most basic features found in a desktop computer. A smaller, lighter laptop computer is called a **notebook**.

Palmtop computers serve a specialized niche, allowing access to some of the same information available from a laptop, but in a much smaller package. Palmtops may have no keys, or very small keys that are much smaller than the standard keyboard.

Personal digital assistants (PDAs) support limited functionality of laptop computers in a notecard-sized format. A typical interface method is a stylus with a graphical touch-sensitive screen; standard functions include a calendar, address book, e-mail, and a calculator. Options include synchronizing hardware to upload address lists or e-mail to a PC, and a modem for portable Internet access. Some models combine the functionality of a PDA with a cell phone and a digital camera.

Calculators and organizers are available usually for fixed arithmetic functions and, on the high end, programmable applications. This hardware format is typically inexpensive and portable, but software is typically proprietary. Laptops, palmtops, and PDAs have challenged the advantages of calculators and organizers.

COMPUTER SOFTWARE

Software is computer instructions or data that can be stored electronically in storage hardware, such as random access memory (RAM), or secondary memory such as hard disk drives, DVDs, or CDs.

Software is often divided into two categories:

- *Systems software* includes the operating system and utilities associated with the operating system, such as file copying.
- *Applications software* includes the programs used to do the user's work, such as word processors, spreadsheets, or databases. HVAC-specific programs belong to the applications software category.

Operating Systems

The operating system (OS) is the basic control program that allows execution and control of application software. Operating systems (system software) also provide a common environment for applications to use shared resources such as memory, secondary storage (e.g., hard disk storage), processing time, network access, the keyboard, graphic display environments, desktops, file services, and

printer services. Application software must be selected first; that decision will typically limit the hardware computer platform and OS.

Utility Software

Utility programs perform a wide variety of organizing and data-handling operations such as copying files, printing files, file management, network analysis, disk size utilities, CPU speed tests, improving security, and other related operations. Most utilities perform one or two specific functions.

Compression Software. These utilities compress and archive data files in a standard format, such as ZIP. Compression utilities allow files and file systems to be compressed, making the transfer of information and files much more efficient without any loss of content or data. These utilities are valuable when file size is important, such as transmitting files over a limited-bandwidth communication system, and for archival purposes. A typical compression ratio for text files is 3:1. E-mail attachments are often compressed.

Antivirus Software. An important software package for most computer systems is antivirus software (see the section on E-mail, Viruses, and Hoaxes). Antivirus software detects, quarantines, repairs, and eliminates files that contain viruses. A computer virus may take various forms and is commonly attached invisibly to a word-processed or e-mailed document. Antivirus software is imperative when a computer is accessing Internet-based information. Antivirus software must be updated frequently to be able to identify new viruses. Updates are often available free of charge after purchasing antivirus software.

Antispyware Software. Spyware is a type of program that sends information from your computer to another computer, usually with malicious intent. It may send passwords, credit card numbers, or any other information that is typed into your computer. Antispyware software will detect spyware and remove it.

Firewall Software. A firewall is a utility that controls and limits all network communications going from or to your computer. With a firewall, only programs with permission are allowed to communicate over the network. This should stop spyware and other similar malicious programs. Also, a firewall limits the communications it accepts over the network, which acts against other types of attacks. Large organizations generally have a firewall separating their entire network from the Internet, but it is still important to have a firewall on each PC.

Back-Up Software. The ability to recover from a massive failure such as a successful virus attack, accidental deletion of files, flood, fire, hardware (especially hard disk) failure, and other inevitable disasters is extremely important. Typically, information service (IS) computers use a rotating digital tape back-up strategy that performs massive back-ups of network resources. Individual computers may not be included in these back-ups, so regularly scheduled back-ups must be performed. A relatively inexpensive way to back up small amounts of data is to store data files and documents in a compact disk recordable (CD-R) format, which allows roughly up to 700 MB of storage at low cost. Digital versatile disks (DVDs) offer roughly 10 times the storage capacity of CD-R. Tape back-up provides an extremely low cost per megabyte stored and is useful if quick access and retrieval of individual back-up files is not an issue. Back-ups should be stored in a secure location away from the computer system. There are two basic types of back-ups: complete, in which all files are backed up, or incremental, in which only files changed since the last back-up are stored. A typical strategy is to perform a complete back-up once a week or month, and to perform an incremental back-up every day.

Application Software

Some useful application software falls into one of these categories:

Word Processing. Word processing applications are used for tasks that range from creating simple printable documents to

providing products for advanced enterprise-level electronic distribution and publishing systems. Features may include automatic text layout, spellchecking, printing, index and table of contents generation, simple graphics, and the ability to save files in a variety of formats such as rich text format (RTF), hypertext markup language (HTML), plain text, or American Standard Code for Information Interchange (ASCII). Most word processors allow the user to view the output before printing.

Specification Writing. A useful extension to word processors is application software to create specifications for the consulting engineer. Features include ensuring selectable sections for creating desired features, and consistent naming of materials, specifications, and processes or sequences.

Specification software can save time by allowing the reuse of sections from a master specification, along with previously developed specification details, sometimes with small changes. Specification tools are most useful in situations that do not require completely new specifications from project to project.

Desktop Publishing. This is a specialized class of word processors with high-end, professional text and graphics layout features. Desktop publishing systems have been extended to incorporate professional-quality graphical images, many different styles of text and fonts, and special effects such as color fading, shadowing, and artistic effects. Using inexpensive, high-quality printers, the quality of output from desktop publishing software can be remarkable. In general, the limiting factor in the use of desktop publishing software is the time and training investment to use it efficiently.

Web Publishing. Word processors are best suited for printing documents on paper; Web publishing tools are designed to format information and transfer the documents to Web sites. In many regards, Web publishing software is similar to word processing software, allowing text, graphics, and tables to be formatted for display. Unique extensions from Web software include the ability to manage links, or connections within a related collection of documents.

Web publishing software saves information in HTML, a standard format used by Web browsers. Web browsers can display information in many different screen resolutions and sizes, which makes a standard layout of documents especially difficult.

Other features of Web publishing software include tools to enforce consistency of Web page format and style, lower resolution of pictures and graphics to reduce loading time, and preview what the final Web page will look like to the end user.

Standardized Web Document Formats. Created as a result of special formatting requirements for printing and display on Web pages, this software converts word processing documents to a standard format. This standard format requires the use of a Web browser software extension called a "plug-in," typically offered at no charge as a viewing tool. The viewing tool allows users to see and print the document in exactly the same format. The disadvantage of standardized formats is the inability to modify the information.

Spreadsheets. Spreadsheet applications allow the user to create tables for adding and subtracting columns of numbers in one complete view. Spreadsheets contain thousands of cells into which the user may enter labels, numbers, formulas, or even programs ("macros") to execute such functions as subroutines for a specific calculation, database sorting and searching, conversions, and other calculations. Automatic recalculations allow displayed information to be evaluated quickly. Spreadsheets are useful for importing and formatting data into a graphical display, trend analysis, and/or statistical computations. Users can input different variable values into a mathematical representation of the process or system, and evaluate the results immediately or save them as separate files of graphs for later analysis.

Databases. Database applications are designed to store, organize, and sort information in a specialized format optimized for speed and utility. Simple PC database applications are typically designed for single users, whereas database management systems (DBMSs) are designed for larger applications involving multiple-user access. DBMSs support security hierarchies, record and file locking, and mission-critical network-accessible applications such as financial and banking applications. The standard language for accessing the database information is structured query language (SQL).

Presentations. Software optimized for group presentations displays information on digital projection systems. Presentation software is able to present simple text and graphics in an attractive screen format package for seminars, demonstrations, and training. Additionally, most presentation software allows the creation of notes for the speaker to consult during the presentation, and slide handouts. Popular extensions to presentation software include sound effects and multimedia effects such as video and audio clips. Libraries of vendor and third-party graphics are available at extra charge or from the Internet.

Accounting. Accounting software for accounts receivable, accounts payable, payroll, and taxes is available for many hardware platforms. Many accounting software packages contain extra modules and applications that allow extensions for unique accounting requirements. Financial reports for projects can be easily generated from standard report packages. Large accounting systems can be integrated with databases and automatic tax-reporting functions. Individual accounts and corrections can be monitored and updated automatically. Large accounting systems also allow integration and reporting from individual employees via Web browser applications.

Project Scheduling. Meeting project requirements and efficiently coordinating project resources are difficult tasks; project scheduling software helps solve these problems. Most project scheduling software can take resources (such as individual workers), length of task, percent allocation of resources, and task interdependencies, and present the information as a critical path method (CPM) chart or as a program evaluation and review technique (PERT) chart to evaluate the schedule. Many applications can perform resource leveling, resulting in an efficient allocation of resources to complete the project.

As project scheduling software is updated to include real data, the predicted completion date and the total amount of resources used (e.g., hours worked on individual tasks, material requirements) can be used as predictive record for future projects.

Management. Management software can review past and current data on inventory, accounting, purchasing, and project control, and predict future performance. As more data are accumulated, statistical analysis can predict performance with a specified level of confidence.

Much of the data required for these techniques may require access to standard industry data in industry-wide databases, financial forecasts, code standards, and demographic and other resources. In many cases, this information can be obtained on the Internet for a nominal fee.

Web Meetings. Similar to teleconferences, Web meetings coordinate demonstrations and meetings over the Internet. Participants use a common Web site to view and update a slide show presentation, with optional voice commentary handled either through traditional teleconferencing or through streaming audio or video feeds. Some types allow participants to view the desktop of the moderator's computer, allowing them to share a live view of any application the moderator chooses.

Graphics and Imaging. Graphics software packages readily produce images, x-y charts, graphs, pie charts, and custom graphics. Libraries of graphics and images exist for use in word processing, presentation, desktop publishing, and Web page applications. Many graphics programs can produce output in numerous popular computer graphics formats such as Joint Photographic Experts Group (JPG), graphics interchange format (GIF), tagged information file

format (TIFF), bitmap (BMP), and other standards. Specialty programs allow graphics files to be converted between graphics formats. Multimedia tools allow video and sound to be combined with traditional text and graphics.

Images require large amounts of data to be represented accurately. Graphics are usually stored in either bitmap or vector format. The **bitmap** format is commonly used for picture and photo-oriented graphics, whereas **vector** formats are commonly used in CAD/CAM and architectural drawings. Although the output of bitmap images is simple on devices such as graphic printers, rescaling these images does not always produce satisfactory output. Conversions between formats give varying results. Bitmap images are frequently converted to JPG (typically for photographic images) and GIF (typically for simple drawings) file formats.

Web Browsers. Most Internet-enabled computers have Web browsers that support text and graphical Web page displays. The underlying language of the World Wide Web is HTML, and navigation is by clicking on links to access different computer systems and pages on the Web.

Browsers are a preferred interface for accessing vastly different computer systems. Full-feature browsers also support Java® applets (small programs) and a host of extension applications that are available at nominal or no charge. These include streaming sound, streaming multimedia, and graphics formats other than GIF and JPG, which are natively supported by browsers. Some other available features include access to e-mail, file transfer protocol (FTP; for transferring files to and from servers over the Internet), chat rooms, newsgroups and forums, Telnet access to computers, and access to secure e-commerce sites that use encryption routines to protect sensitive data such as credit card information, bank account balances, and stock transfer information.

SOFTWARE AVAILABILITY

Freeware is copyrighted software that is free. The user can run the software, but must obey the copyright restrictions.

Public domain software is available to the public for little or no charge. Public domain software, which is not copyrighted, is often confused with freeware, which is copyrighted. Public domain software can be used without the restrictions associated with copyrighted software.

Shareware is software available for users to try before buying it; after the trial period, users are expected to register or stop using the application. There is usually a nominal registration fee.

Software can be **purchased** from manufacturers, distributors, representatives, discount stores, and computer specialty stores. Software price, support, return policies, and distribution vary from vendor to vendor. During installation, most software displays a detailed software license granting *use* rather than *ownership* of the software program. This license gives specific restrictions on how the software is to be used. Most high-volume software does not offer direct support, but many software companies offer pay-per-incident and other fee arrangements if desired. Many applications have discussion groups or message boards on the Internet, where solutions to problems may be found. Most off-the-shelf, shrinkwrapped software is nonreturnable once opened.

CUSTOM PROGRAMMING

Using an existing software package is usually preferable to designing a custom application, which is much more expensive and potentially riskier, especially for large, mission-critical software such as client-server applications. If, after careful evaluation, prepackaged software will not suffice, the choice must be made between in-house and outside development. Custom software can be (1) contracted out to a specialized firm, (2) developed solely by internal staff, or (3) developed by internal staff with consultation help by an outside firm.

Contracting to an outside firm involves hiring a specialized outside party to define, estimate, schedule, and create the software. Funds should be budgeted for the outside organization to support modifications or enhancements not specifically covered in the contract. Contracting outside is suitable for an organization that does not have the resources or expertise to accomplish the project. Disadvantages of this approach include the expense and lack of control over the program. Licensing and ownership issues must be defined in the contract.

Developing the program internally is viable only if the skills and resources are available. Internal projects are easier to control because the people involved are co-located.

Consultation help from an outside firm involves a skilled outside party assisting internal staff, who may have insufficient skill in the area on their own. Outside firms can provide expertise to get a project going quickly. Long-term support and maintenance of the software are done in-house.

Specifications are key to the success of a software project. Calculations, human interface, reports, user documents, and testing procedures should be carefully detailed and agreed on by all parties before development begins. Software testing should be specified at the beginning of the project to avoid the common problem of low quality because of hasty and inadequate testing. Design testing should address the human interface, a wide range of input values including improper input, the various functions, and output to screen, disk, or other media. Field tests should include conditions experienced by the final users of the software.

With any development approach, good, understandable documentation is required. If for any reason the software cannot be adequately supported, the program will have to be replaced at substantial cost.

SOFTWARE LANGUAGES

Application software is written in a variety of computer languages. Most commercial software today is written in C++ or C to allow fast speed and efficient use of resources.

Visual Basic® is an extremely popular and easy-to-use graphical programming language for Windows® that has proprietary extensions of the original BASIC language. High-performance software modeling tools such as finite element analysis (FEA) and graphics modeling use Fortran and C.

Several modern languages, such as Java® and Smalltalk, use object-oriented programming. Java is a favored programming language for applications that run over computer networks such as the Internet. C++ mixes both traditional procedural C language programming and object-oriented extension concepts. The major disadvantage of Java and C++ is the high level of programming skill required to create programs.

Java is a powerful programming language and environment with extensions to support Internet, security, and multiplatform implementation. Java applets are small, secure, self-contained programs that need a host environment, such as a Web browser, to run. Many new applications use standard Web browsers with applets to create useful displays and interfaces. JavaBeans are modular components that provide users with standard modular and graphical interfaces of components. Enterprise JavaBeans (EJB) are server-based programs that allow interoperability and language standardization to be scalable and interchangeable between server vendors.

Relational system databases use structured query language (SQL). Object databases are still relatively new, but fully support the object-oriented paradigm of object references, instead of the traditional relational model.

INPUT/OUTPUT (I/O) DEVICES

Basic computer peripherals (e.g., monitor, keyboard, mouse, etc.) allow interaction with the computer and are sufficient for many applications. More advanced I/O capability is available through digital cameras, scanners, bar code readers, stylus pads, voice recognition devices, and fax machines. Common devices include the following.

Printer types include laser and ink-jet. Laser printers offer a lower cost per sheet, double-sided printing, faster throughput, and large storage capacity. Ink-jet printers offer color printing and lower initial cost but have a higher operating cost.

CD and DVD drives can be used to read data from a CD or DVD. CD and DVD burners can be used to write data to a new CD or DVD, or to make a copy of an existing one. There are two types of writeable disks: CD-R (DVD+/–R) and CD-RW (DVD+/–RW). Once data is written to a CD-R or DVD+/–R, it cannot be changed. Data written to a CD-RW or DVD+/–RW can be modified or deleted, like data on a floppy disk.

Digital cameras are useful for photographs and digital storage of images. These digitized images can be transmitted electronically and viewed or incorporated into Web or traditional documents. Most digital cameras can store dozens or hundreds of pictures, depending on the memory provided. Some can also store up to several minutes of video. PC video cameras allow a live image such as live conferencing to be viewed and recorded. A cell phone with a digital camera may allow users to transmit (e-mail) pictures from any location where there is cell phone service.

Scanners digitize printed photographs and images, and have a characteristic image quality expressed in dots per inch (dpi). The image files can be large and should preferably be stored using a compression format such as JPG. Special scanner software can also read text from a scanned document through a process called optical character recognition (OCR). The scanned text can then be viewed or edited in a word processor.

Bar code readers speed database input by converting a manual scan of a bar code to the alphanumeric input in a database field.

Stylus pads combine the navigational functionality of a mouse with the ability to enter handwritten notes and sketches and run automated scripts based on movements on the pad.

Voice recognition software automatically converts speech to typed text. These programs take some tuning to learn the accent, diction, and idioms of the user. Many voice recognition software packages also enable automated scripts or macros to run on verbal commands.

Fax software emulates a printer driver. It allows the user to print a document to a target fax machine through a modem. It also allows the user to receive faxes as electronic documents. Other features include integration with electronic contact databases, templates for transmittal pages, and automated tracking of faxes sent and received.

HVAC SOFTWARE APPLICATIONS

Over the past decade, the use of computer software designing mechanical systems has increased. The advantages of software-assisted design over traditional manual methods include the following:

- Computers can better preserve design assumptions and document the design intent through consolidating and organizing resources (e.g., central databases, Web sites with design documents)
- It is often faster and easier to modify assumptions used in a calculation and recalculate the results using a computer
- The computational speed of computers allows designers to tackle more difficult design problems and to use more accurate (but computationally intensive) methods
- Computers assist designers in analyzing design alternatives.

In the future, interoperable software design and application of expert systems could reduce the burden of design. Interoperable applications automatically pass design assumptions and calculation results between applications, reducing both the burden of user input and the opportunity for user error. Expert and rule-based systems could automate design standards to the point where simple system selection or distribution system sizing can be automated.

There is a wide variety of software used in the HVAC industry. This section covers applications that assist mechanical engineers in design, analysis, and specification of mechanical systems, including

- HVAC design software
- HVAC simulation software
- CAD/graphics software
- Miscellaneous utilities and applets

Much of this software is also used by HVAC equipment manufacturers to design their products, and by controls contractors to develop control systems.

In addition, sources for these applications and the fundamentals of interoperable computer applications for the HVAC&R industry are discussed.

The distinction between HVAC design and simulation is subtle. The convention used here is that design software is used for static analysis: evaluating equipment and distribution systems under a specific design condition. In contrast, HVAC simulation is used for dynamic system analysis over a range of time or operating conditions. Many applications provide both functions through a single interface.

HVAC DESIGN CALCULATIONS

HVAC design software includes programs for the following tasks:

- HVAC heating and cooling load calculations
- Duct system sizing and analysis
- Pipe system sizing and analysis
- Acoustical analysis
- Equipment selection

Although computers are now widely used in the design process, most programs perform analysis, not design, of a specified system. That is, the engineer proposes a design and the program calculates the consequences of that design. When the engineer can define alternatives, a program may aid design by analyzing performance of the alternatives and then selecting the best according to predetermined criteria. Thus, a program to calculate the cooling load of a building requires specifications for the building and its systems; it then simulates that building's performance under certain conditions of weather, occupancy, and scheduling. Although most piping and duct design tools can size pipe or ductwork based on predetermined criteria, most engineers still decide duct dimensions, air quantities, duct routing, and so forth and use software to analyze the performance of that design.

Some interoperable software can pass values from one design phase to be used as inputs in the next. For example, a load program may be used to determine the design air quantities at the zone and space level. Through interoperability, this information can be preserved in the building model and used as an input for the duct sizing program. Interoperable software is further described in the section on Interoperable Computer Applications for the HVAC&R Industry.

Because computer programs perform repetitive calculations rapidly, the designer can explore a wide range of alternatives and use selection criteria based on annual energy costs or life-cycle costs.

Heat and Cooling Load Design

Calculating design thermal loads in a building is a necessary step in selecting HVAC equipment for virtually any building project. To

ensure that heating equipment can maintain satisfactory building temperature under all conditions, peak heating loads are usually calculated for steady-state conditions without solar or internal heat gains. This relatively simple calculation can be performed by hand or with a computer.

Peak cooling loads are more transient than heating loads. Radiative heat transfer within a space and thermal storage cause thermal loads to lag behind instantaneous heat gains and losses. This lag can be important with cooling loads, because the peak is both reduced in magnitude and delayed in time compared to the heat gains that cause it. A further complication is that loads peak in different zones at different times (e.g., the solar load in a west-facing zone will peak in the afternoon, and an east-facing zone will usually peak in the morning). To properly account for thermal lag and the noncoincidence of zone loads, a computer program is generally required to calculate cooling loads for a multiple-zone system. These programs simulate loads for each hour of the day for every day of the year (or a representative subset of the days of the year), and report peak loads at both the zone and system level, recording the date and time of their occurrence. Because the same input data are used for heating and cooling loads, these programs report peak heating loads, as well.

Various calculation methods are used to account for the transience of cooling loads; the most common methods are described in detail in Chapters 29 and 30 of the 2005 *ASHRAE Handbook—Fundamentals*. The most accurate but computationally intensive method, the heat-balance method, is a fundamental calculation of heat transfer from all sources with the construction elements of the building (walls, floor, windows, skylights, furniture, ceiling, slab, and roof). Only the computational speed of present-day personal computers allows these calculations to be performed for large multizone buildings in a reasonable amount of time (ranging from several minutes to an hour or more). Several simplified methods or approximations of thermal lag are available to speed computation time, including the radiant time-series (RTS), transfer function (TFM), total equivalent temperature differential with time averaging (TETD/TA) and cooling load temperature differential with cooling load factors (CLTD/CLF) methods. These approximations are less accurate than the heat balance method, but can be sufficient if they are appropriately applied.

Both the TETD/TA and the TFM methods require a history of thermal gains and loads. Because histories are not initially known, they are assumed zero and the building under analysis is taken through a number of daily weather and occupancy cycles to establish a proper 24 h load profile. Thus, procedures required for these methods involve so many individual calculations that noncomputerized calculations are highly impractical. The CLTD/CLF method, on the other hand, is meant to be a manual calculation method and can be implemented by a spreadsheet program. The CLTD and CLF tables presented in the 2001 *ASHRAE Handbook—Fundamentals* are, in fact, based on application of the TFM to certain geometries and building constructions. An automated version of TFM is preferred to CLTD/CLF because it is more accurate. The automated TETD/TA method, however, can provide a good approximation with significantly less computation than the TFM.

Characteristics of a Loads Program. In general, a loads program requires user input for most or all of the following:

- Full building description, including the construction and other heat transfer characteristics of the walls, roof, windows, and other building elements; size; orientation; geometry of the rooms, zones, and building; and possibly also shading geometries
- Sensible and latent internal loads from lights and equipment, and their corresponding operating schedules
- Sensible and latent internal loads from people
- Indoor and outdoor design conditions
- Geographic data such as latitude and elevation
- Ventilation requirements and amount of infiltration

- Number of zones per system and number of systems

With this input, loads programs calculate both the heating and cooling loads and perform a psychrometric analysis. Output typically includes peak room and zone loads, supply air quantities, and total system (coil) loads.

Selecting a Loads Program. Beyond general characteristics, such as hardware and software requirements, type of interface (icon-based, menu-driven versus command-driven), availability of manuals and support, and cost, some program-specific characteristics should be considered when selecting a loads program. The following are among items to be considered:

- Ease of use and compatibility with the existing operating system
- Type of building to be analyzed: residential versus commercial (residential-only loads programs tend to be simpler to use than more general-purpose programs meant for commercial and industrial use, but residential-only programs generally have limited abilities)
- Method of calculation for the cooling load (note that some programs support more than one method of calculation)
- Program limits on such items as number of systems, zones, rooms, and surfaces per room
- Sophistication of modeling techniques (e.g., capability of handling exterior or interior shading devices, tilted walls, daylighting, skylights, etc.)
- Units of input and output
- Program complexity (in general, the more sophisticated and flexible programs require more input and are somewhat more difficult to use than simpler programs)
- Capability of handling the system types under investigation
- Certification of the program for energy code compliance
- Ability to share data with other programs, such as CAD and energy analysis

Duct Design

Chapter 35 of the 2005 *ASHRAE Handbook—Fundamentals* describes several methods for duct design. Major considerations in duct design include the physical space required by the duct, cost of the ductwork and fittings, energy required to move air through the duct, acoustics, minimum velocities to maintain contaminants in suspension (fume exhaust), flexibility for future growth, zoning, and constructability. Duct software can help with the layout and analysis of new and/or existing distribution systems.

Duct design is more an art than a science, which complicates automation of design. Duct design programs and calculation methods are limited in their ability to (1) calculate actual operating pressures because of the impact of fan and duct system effects, and (2) take into consideration many unmeasurable factors in the process of laying out and sizing ducts (e.g., provision for space limitations, local duct construction preferences and practices, local labor and material costs, acoustics, and accommodating future remodeling).

Selecting and Using a Program. Duct design involves routing or laying out ductwork, selecting fittings, and sizing ducts. Computer programs can rapidly analyze design alternatives and determine critical paths in long and complicated distribution systems. Furthermore, programs and printouts can preserve the assumptions used in the design: any duct calculation requires accurate estimates of pressure losses in duct sections and the definition of the interrelations of velocity heads, static pressures, total pressures, and fitting losses.

The general computer procedure is to designate nodes (the beginning and end of duct sections) by number. Details about each node (e.g., divided flow fitting and terminal) and each section of duct between nodes (maximum velocity, flow rate, length, fitting codes, size limitation, insulation, and acoustic liner) are used as input data (Figure 1).

Characteristics of a duct design program include the following:
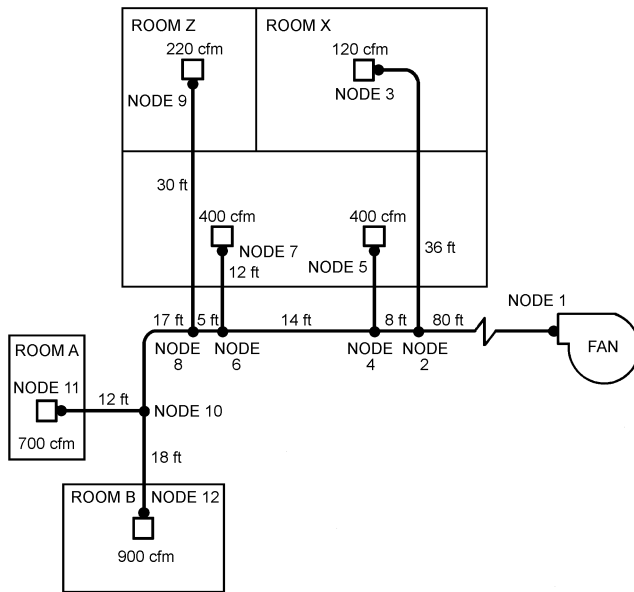
Fig. 1   Example of Duct System Node Designation

- Calculations for supply, return, and exhaust
- Sizing by constant friction, velocity reduction, static regain, and constant velocity methods
- Analysis of existing ducts
- Inclusion of fitting codes for a variety of common fittings
- Identification of the duct run with the highest pressure loss, and tabulation of all individual losses in each run
- Printout of all input data for verification
- Provision for error messages
- Calculation and printout of airflow for each duct section
- Printout of velocity, fitting pressure loss, duct pressure loss, and total static pressure change for each duct section
- Graphics showing schematic or line diagrams indicating duct size, shape, flow rate, and air temperature
- Calculation of system heat gain/loss and correction of temperatures and flow rates, including possible system resizing
- Specification of maximum velocities, size constraints, and insulation thicknesses
- Consideration of insulated or acoustically lined duct
- Bill of materials for sheet metal, insulation, and acoustic liner
- Acoustic calculations for each section
- File-sharing with other programs, such as spreadsheets and CAD

Because many duct design programs are available, the following factors should be considered in program selection:

- Maximum number of branches that can be calculated
- Maximum number of terminals that can be calculated
- Types of fittings that can be selected
- Number of different types of fittings that can be accommodated in each branch
- Ability of the program to balance pressure losses in branches
- Ability to handle two- and three-dimensional layouts
- Ability to size a double-duct system
- Ability to handle draw-through and blow-through systems
- Ability to prepare cost estimates
- Ability to calculate fan motor power
- Provision for determining acoustical requirements at each terminal
- Ability to update the fitting library

Optimization Techniques for Duct Sizing. For an optimized duct design, fan pressure and duct cross sections are selected by minimizing the life-cycle cost, which is an objective function that
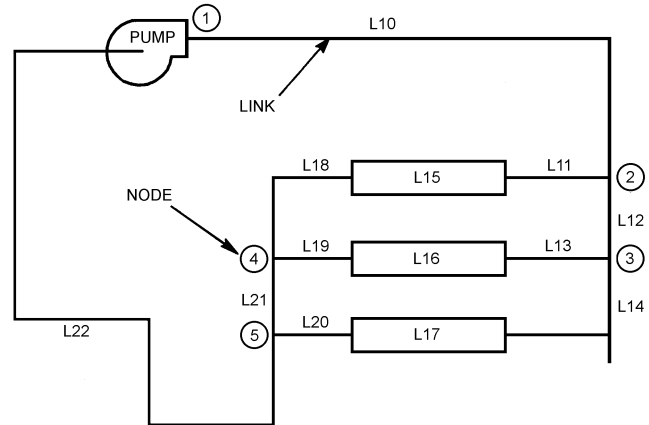
Fig. 2   Examples of Nodes for Piping System

includes initial and energy costs. Many constraints, including constant pressure balancing, acoustic restrictions, and size limitations, must be satisfied. Duct optimization is a mathematical problem with a nonlinear objective function and many nonlinear constraints. The solution must be taken from a set of standard diameters and standard equipment. Numerical methods for duct optimization exist, such as the T method (Tsal et al. 1988), coordinate descent (Tsal and Chechik 1968), Lagrange multipliers (Kovarik 1971; Stoecker et al. 1971), dynamic programming (Tsal and Chechik 1968), and reduced gradient (Arkin and Shitzer 1979).

Piping Design

Many computer programs are available to size or calculate the flexibility of piping systems. Sizing programs normally size piping and estimate pump requirements based on velocity and pressure drop limits. Some consider heat gain or loss from piping sections. Several programs produce a bill of materials or cost estimates for the piping system. Piping flexibility programs perform stress and deflection analysis. Many piping design programs can account for thermal effects in pipe sizing, as well as deflections, stresses, and moments.

Numerous programs are available to analyze refrigerant piping layouts. These programs aid in design of properly sized pipes or in troubleshooting existing systems. Some programs are generic, using the physical properties of refrigerants along with system practices to give pipe sizes that may be used. Other programs "mix and match" evaporators and condensers from a particular manufacturer and recommend pipe sizes. See Chapter 2 of the 2006 *ASHRAE Handbook—Refrigeration* for specifics on refrigerant pipe sizing.

The general technique for computerizing piping design problems is similar to that for duct design. A typical piping problem in its nodal representation is shown in Figure 2.

Useful piping programs do the following:

- Provide sufficient design information
- Perform calculations for both open and closed systems
- Calculate flow, pipe size, and pressure drop in each section
- Handle three-dimensional piping systems
- Cover a wide selection of common valves and fittings, including specialized types (e.g., solenoid and pressure-regulating valves)
- Consider different piping materials such as steel, copper, and plastic by including generalized friction factor routines
- Accommodate liquids, gases, and steam by providing property information for a multiplicity of fluids
- Calculate pump capacity and head required for liquids
- Calculate available terminal pressure for nonreturn pipes
- Calculate required expansion tank size
- Estimate heat gain or loss for each portion of the system

- Prepare a cost estimate, including costs of pipe and insulation materials and associated labor
- Print out a bill of materials
- Calculate balance valve requirements
- Perform a pipe flexibility analysis
- Perform a pipe stress analysis
- Print out a graphic display of the system
- Allow customization of specific design parameters and conditions, such as maximum and minimum velocities, maximum pressure drops, condensing temperature, superheat temperature, and subcooling temperature
- Allow piping evaluation for off-design conditions
- Provide links to other programs, such as equipment simulation programs

Limiting factors to consider in piping program selection include the following:

- Maximum number of terminals the program can accommodate
- Maximum number of circuits the program can handle
- Maximum number of nodes each circuit can have
- Maximum number of nodes the program can handle
- Compressibility effects for gases and steam
- Provision for two-phase fluids

Acoustic Calculation

Chapter 47 summarizes sound generation and attenuation in HVAC systems. Applying these data and methodology often requires a large amount of computation. All sound-generation mechanisms and transmission paths are potential candidates for analysis. Adding to the computational work load is the need to extend the analysis over, at a minimum, octave bands 1 through 8 (63 Hz through 8 kHz). A computer can save a great amount of time and difficulty in the analysis of any noise situation, but the HVAC system designer should be wary of using unfamiliar software.

Caution and critical acceptance of analytical results are necessary at all frequencies, but particularly at low frequencies. Not all manufacturers of equipment and sound control devices provide data below 125 Hz; in such cases, the HVAC designer conducting the analysis and the programmer developing the software must make experience-based assumptions for these critical low-frequency ranges.

The designer/analyst should be well satisfied if predictions are within 5 dB of field-measured results. In the low-frequency "rumble" regions, results within 10 dB are often as accurate as can be expected, particularly in areas of fan discharge. Conservative analysis and application of results is necessary, especially acoustically critical spaces.

Several easy-to-use acoustics programs are currently available, but they are often less detailed than custom programs developed by acoustic consultants for their own use. Acoustics programs are designed for comparative sound studies and allow the design of comparatively quiet systems. Acoustic analysis should address the following key areas of the HVAC system:

- Sound generation by HVAC equipment
- Sound attenuation and regeneration in duct elements
- Wall and floor sound attenuation
- Ceiling sound attenuation
- Sound breakout or break-in in ducts or casings
- Room absorption effect (relation of sound power criteria to sound pressure experienced)

Algorithm-based programs are preferred because they cover more situations (see Chapter 47); however, algorithms require assumptions. Basic algorithms, along with sound data from the acoustics laboratories of equipment manufacturers, are incorporated to various degrees in acoustics programs. The HVAC equipment sound levels in acoustics programs should come from the manufacturer and be based on measured data, because there is a wide variation in the sound generated by similar pieces of equipment. Some generic equipment sound generation data, which may be used as a last resort in the absence of specific measured data, are found in Chapter 47. Whenever possible, equipment sound power data by octave band (including 32 Hz and 63 Hz) should be obtained for the path under study. A good sound prediction program relates all performance data.

Many more specialized acoustics programs are also available. Various manufacturers provide equipment selection programs that not only select optimum equipment for a specific application, but also provide associated sound power data by octave bands. Data from these programs should be incorporated in the general acoustic analysis. For example, duct design programs may contain sound predictions for discharge airborne sound based on the discharge sound power of fans, noise generation/attenuation of duct fittings, attenuation and end reflections of VAV terminals, attenuation of ceiling tile, and room effect. VAV terminal selection programs generally contain subprograms that estimate the space NC level near the VAV unit in the occupied space. However, projected space NC levels alone may not be acceptable substitutes for octave-band data. The designer/analyst should be aware of assumptions, such as room effect, made by the manufacturer in presenting acoustical data.

Predictive acoustic software allows designers to look at HVAC-generated sound in a realistic, affordable time frame. HVAC-oriented acoustic consultants generally assist designers by providing cost-effective sound control ideas for sound-critical applications. A well-executed analysis of the various components and sound paths enables the designer to assess the relative importance of each and to direct corrective measures, where necessary, to the most critical areas. However, computer-generated results should supplement the designer's skills, not replace them.

Equipment Selection and Simulation

Equipment-related computer applications include programs for equipment selection, equipment optimization, and equipment simulation.

Equipment selection programs are basically computerized catalogs. The program locates an existing equipment model that satisfies the entered criteria. The output is a model number, performance data, and sometimes alternative selections.

Equipment optimization programs display all possible equipment alternatives and let the user establish ranges of performance data or first cost to narrow the selection. The user continues to narrow performance ranges until the best selection is found. The performance data used to optimize selections vary by product family.

Equipment simulation programs calculate the full- and part-load performance of specific equipment over time, generally one year. The calculated performance is matched against an equipment load profile to determine energy requirements. Utility rate structures and related economic data are then used to project equipment operating cost, life-cycle cost, and comparative payback. Before accepting output from an equipment simulation program, the user must understand the assumptions made, especially concerning load profile and weather.

Some advantages of equipment programs include the following:

- High speed and accuracy of the selection procedure
- Pertinent data presented in an orderly fashion
- More consistent selections than with manual procedures
- More extensive selection capability
- Multiple or alternative solutions
- Small changes in specifications or operating parameters easily and quickly evaluated
- Data-sharing with other programs, such as spreadsheets and CAD

Simulation programs have the advantages of (1) projecting part-load performance quickly and accurately, (2) establishing minimum

part-load performance, and (3) projecting operating costs and offering payback-associated higher-performance product options.

There are programs for nearly every type of HVAC equipment, and industry standards apply to the selection of many types. The more common programs and their optimization parameters include the following:

Air distribution units	Pressure drop, first cost, sound, throw
Air-handling units, rooftop units	Power, first cost, sound, filtration, footprint, heating and cooling capacity
Boilers	First cost, efficiency, stack losses
Cooling towers	First cost, design capacity, power, flow rate, air temperatures
Chillers	Power input, condenser head, evaporator head, capacity, first cost, compressor size, evaporator size, condenser size
Coils	Capacity, first cost, fluid pressure drop, air pressure drop, rows, fin spacing
Fan coils	Capacity, first cost, sound, power
Fans	Volume flow, power, sound, first cost, minimum volume flow
Heat recovery equipment	Capacity, first cost, air pressure drop, water pressure drop (if used), effectiveness
Pumps	Capacity, head, impeller size, first cost, power
Air terminal units (variable and constant volume flow)	Volume flow rate, air pressure drop, sound, first cost

Some extensive selection programs have evolved. For example, coil selection programs can select steam, hot-water, chilled-water, and refrigerant (direct-expansion) coils. Generally, they select coils according to procedures in ARI *Standards* 410 and 430.

Chiller and refrigeration equipment selection programs can choose optimal equipment based on factors such as lowest first cost, highest efficiency, best load factor, and best life-cycle performance. In addition, some manufacturers offer modular equipment for customization of their product. This type of equipment is ideal for computerized selection.

However, equipment selection programs have limitations. The logic of most manufacturers' programs is proprietary and not available to the user. All programs incorporate built-in approximations or assumptions, some of which may not be known to the user. Equipment selection programs should be qualified before use.

HVAC SIMULATION

Energy Simulation

Unlike peak load calculation programs, building energy simulation programs integrate loads over time (usually a year), consider the systems serving the loads, and calculate the energy required by the equipment to support the system. Most energy programs simulate the performance of already designed systems, although programs are now available that make selections formerly left to the designer, such as equipment sizes, system air volume, and fan power. Energy programs are necessary for making decisions about building energy use and, along with life-cycle costing routines, quantify the effect of proposed energy conservation measures during the design phase. In new building design, energy programs help determine the appropriate type and size of building systems and components; they can also be used to explore the effects of design tradeoffs and evaluate the benefits of innovative control strategies and the efficiency of new equipment.

Energy programs that track building energy use accurately can help determine whether a building is operating efficiently or waste-fully. They have also been used to allocate costs from a central heating/cooling plant among customers of the plant. However, such programs must be adequately calibrated to measured data from the building under consideration.

Characteristics of Building Energy Simulation. Most programs simulate a wide range of buildings, mechanical equipment, and control options. However, computational results differ substantially across programs. For example, the shading effect from overhangs, side projections, and adjacent buildings frequently affects a building's energy consumption; however, the diverse approaches to load calculation result in a wide range of answers.

The choice of weather data also influences the load calculation. Depending on the requirements of each program, various weather data are used:

- Typical hourly data for one year only, from averaged weather data
- Typical hourly data for one year, as well as design conditions for typical design days
- Reduced data, commonly a typical day or days per month for the year
- Typical reduced data, nonserial or bin format
- Actual hourly data, recorded on site or nearby, for analysis where the simulation is being compared to actual utility billing data or measured hourly data

Simulation programs differ significantly in the methods they use to simulate the mass effects of buildings, ground, and furniture. How accurate these methods are and how well they delay peak heating and cooling can lead to significant uncertainty in predicting building heating and cooling needs, sizing equipment to meet those loads, and predicting system energy needs.

Both air-side and energy conversion simulations are required to handle the wide variations among central heating, ventilation, and air-conditioning systems. To properly estimate energy use, simulations must be performed for each combination of system design, operating scheme, and control sequence.

Simulation Techniques. Two methods are used in computer simulation of energy systems: the fixed schematic technique and the component relation technique.

The **fixed-schematic-with-options technique**, the first and most prevalent method, involves writing a calculation procedure that defines a given set of systems. The schematic is then fixed, with the user's options usually limited to equipment performance characteristics, fuel types, and the choice of certain components.

The **component relation technique** is organized around components rather than systems. Each component is described mathematically and placed in a library. User input includes the definition of the schematic, as well as equipment characteristics and capacities. Once all components have been identified and a mathematical model for each has been formulated, they may be connected and information may be transferred between them. Although its generality leads to certain inefficiencies, the component relation technique does offer versatility in defining system configurations.

Selecting an Energy Program. In selecting an energy analysis program, factors such as cost, availability, ease of use, technical support, and accuracy are important. However, the fundamental consideration is whether the program will do what is required of it. It should be sensitive to the parameters of concern, and its output should include necessary data. For other considerations, see Chapter 32 of the 2005 *ASHRAE Handbook—Fundamentals*.

Time can be saved if the initial input file for an energy program can also be used for load calculations. Some programs interface directly with computer-aided design (CAD) files, greatly reducing the time needed to create an energy program input file.

Comparisons of Energy Programs. Because energy analysis programs use different calculation methods, results vary significantly. Many comparisons, verifications, and validations of simulation

programs have been made and reported (see the Bibliography). Conclusions from these reports can be summarized as follows:

- Results obtained by using several programs on the same building range from good agreement to no agreement at all. The degree of agreement depends on interpretations by the user and the ability of the programs to model the building.
- Several people using several programs on the same building will probably not agree on the results of an energy analysis.
- The same person using different programs on the same building may or may not find good agreement, depending on the complexity of the building and its systems and on the ability of the programs to model specific conditions in that building.
- *Forward* computer simulation programs, which calculate the performance of a building given a set of descriptive inputs, weather conditions, and occupancy conditions, are best suited for design.
- Calibrating hourly forward computer simulation programs is possible, but can require considerable effort for a moderately complex commercial office building. Details on scheduled use, equipment set points, and even certain on-site measurements may be necessary for a closely calibrated model. Special-purpose graphic plots are useful in calibrating a simulation program with data from monthly, daily, or hourly measurements.
- *Inverse*, *empirical*, or *system parameter identification* models may also be useful in determining the characteristics of building energy usage. Such models can determine relevant building parameters from a given set of actual performance data. This is the inverse of the traditional building modeling approach, hence the name.

Energy Programs to Model Existing Buildings. Computer energy analysis of existing buildings can accommodate complex situations; evaluate the energy effects of many alternatives, such as changes in control settings, occupancy, and equipment performance; and predict relative magnitudes of energy use. There are many programs available, varying widely in cost, degree of complexity, and ease of use.

A general input-data acquisition procedure should be followed in computer energy analysis of existing buildings. First, **energy consumption data** must be obtained for a one- to two-year period. For electricity, these data usually consist of metered electrical energy consumption and demand on at least a month-by-month basis. For natural gas, the data are in a similar form and are almost always on a monthly basis. For both electricity and natural gas, it is helpful to record the dates when the meters were read; these dates are important in weather normalization for determining average billing period temperatures. For other types of fuel, such as oil and coal, the only data available may be delivery amounts and dates.

Unless fuel use is metered or measured daily or monthly, consumption for any specific period shorter than one season or year is difficult to determine. Data should be converted to per-day usage or adjusted to account for differences in length of metering periods. The data tell how much energy went into the building on a gross basis. Unless extensive submetering is used, it is nearly impossible to determine when and how that energy was used and for what. It may be necessary to install such meters to determine energy use.

The **thermal and electricity usage characteristics** of a building and its energy-consuming systems as a time-varying function of ambient conditions and occupancy must also be determined. Most computer programs can use as much detailed information about the building and its mechanical and electrical system as is available. Where the energy implications of these details are significant, it is worth the effort of obtaining them. Testing fan systems for air quantities, pressures, control set points, and actions can provide valuable information on deviations from design conditions. Test information on pumps can also be useful.

Data on **building occupancy** are among the most difficult to obtain. Because most energy analysis programs simulate the building

on an hourly basis for a one-year period, it is necessary to know how the building is used for each of those hours. Frequent observation of the building during days, nights, and weekends shows which energy-consuming systems are being used and to what degree. Measured, submetered hourly data for at least one week are needed to begin to understand weekday/weekend schedule-dependent loads.

Weather data, usually one year of hour-by-hour weather data, are necessary for simulation (see Chapter 28 of the 2005 *ASHRAE Handbook—Fundamentals*). The actual weather data for the year in which energy consumption data were recorded significantly improves simulation of an existing building. Where the energy-consuming nature of the building is related more to internal than to external loads, selection of weather data is less important; however, for residential buildings or buildings with large outside air loads, the selection of weather data can significantly affect results. The purpose of the simulation should also be considered when choosing weather data: either specific-year data, data representative of long-term averages, or data showing temperature extremes may be needed, depending on the goal of the simulation.

Usually, the results of the first computer runs do not agree with actual metered energy consumption data. The following are possible reasons for this discrepancy:

- Insufficient understanding of energy-consuming systems that create the greatest use
- Inaccurate information on occupancy and time of building use
- Inappropriate design information on air quantities, set points, and control sequences

The input building description must be adjusted and trial runs continued until the results approximate actual energy use. Matching the metered energy consumption precisely is difficult; in any month, results within 10% are considered adequate.

The following techniques for calibrating a simulation program to measured data from a building should be considered:

- Matching submetered loads or 24 h day profiles of simulated whole-building electric loads to measured data
- Matching *x-y* scatter plots of simulated daily whole-building thermal loads versus average daily temperature to measured data
- Matching simulated monthly energy use and demand profiles to utility billing data

Having a simulation of the building as it is being used permits subsequent computer runs to evaluate the energy effects of various alternatives or modifications. The evaluation may be accomplished simply by changing the input parameters and running the program again. The effect of various alternatives may then be compared and an appropriate one selected.

Computational Flow Dynamics

Computational fluid dynamics (CFD) is a technique for simulation, study, analysis, and prediction of fluid flow and heat transfer in well-defined, bounded spaces. It is based on equations (Navier-Stokes, thermal energy, and species equations, with the appropriate equation of state) that govern the physical behavior of a flow/thermal system, under the premise that mass, momentum, thermal energy, and species concentration are conserved locally and globally within the model.

Usually these equations are in the form of nonlinear partial differential equations relating velocities, pressure, temperature, and some scalar variables to space directions and time. Initial and boundary conditions are specified for each domain, and numerical methods such as finite difference, finite volume, or finite element analysis are utilized to solve these equations. The domain (typically space) is divided (discretized) into cells or elements, the nodal points are defined, then equations are solved for each discrete cell.

After solving these equations, the dependent variables (velocities, pressure, temperature, and scalar) are made available at the nodes.

CFD analysis can be applied to a variety of tasks, including location of airflow inlets/outlets in a space, velocities required for system performance, flow pattern determination, temperature distribution in space, and smoke movement and build-up in a space with fire.

HVAC GRAPHICS, CAD, AND BUILDING DATA MODELS

Computer-Aided Design

Computer graphics of buildings and their systems help coordinate interdisciplinary designs and simplify modifications. CAD (referring to computer-aided drafting at times and to computer-aided design at other times) is a subset of CADD (computer-aided design and drafting). CADD encompasses the creation of **building data models** and the storing and use of attributes of graphic elements, such as automated area takeoff or the storage of design characteristics in a database. Drafting, or the creation of construction documents, is quickly becoming a mere by-product of the design process. The distinction between engineering and drafting in engineering firms is decreasing as design and production work become unified. In this section, CADD refers to all aspects of design.

Building data models express not only true dimensions, but also how different elements are connected and where they are located. Some "intelligent" models can even calculate how different components interact with each other, and how all the components act as a system. It is easy to extract lengths, areas, and volumes, as well as the orientation and connectedness (topology) of building parts from computerized drawings of buildings. Drawings can be changed easily and, in most cases, do not require redrawing construction documents. Building walls or ductwork, for example, can be added, removed, enlarged, reduced, and relocated. The user can rotate an entire building on the site plan without redrawing the building or destroying the previous drawing. Section and elevation views can also be specified and drawn almost instantly, as can fabrication drawings. Building data models can also be exported using standard formats and then imported to other programs, such as those for calculating heating and cooling loads, duct sizing, or operating sheet metal plasma cutting machines.

CAD systems automate (1) material and cost estimating, (2) design and analysis of HVAC systems, (3) visualization and interference checking, and even (4) manufacturing of HVAC components such as ductwork. These systems are now customized to HVAC applications; for instance, double- and single-line duct layout can be re-represented with a single command and automatically generate three-dimensional (3D) building data models.

Computer-generated drawings of building parts can be linked to nongraphic characteristics, which can be extracted for reports, schedules, and specifications. For instance, an architectural designer can draw wall partitions and windows, and then have the computer automatically tabulate the number and size of windows, the areas and lengths of walls, and the areas and volumes of rooms and zones. Similarly, the building data model can store information for later use in reports, schedules, design procedures, or drawing notes. For example, the airflow, voltage, weight, manufacturer, model number, cost, and other data about a fan displayed on a drawing can be stored and associated with the fan in the data model. The link between the graphics and attributes makes it possible to review the characteristics of any item or to generate schedules of items in a certain area on a drawing. Conversely, the graphics-to-data links allow the designer to enhance graphic items having a particular characteristic by searching for that characteristic in the data files and then making the associated graphics brighter, flashing, bolder, or different-colored in the display.

Computer-generated data models can also help the designer visualize the building and its systems and check for interferences, such as structure and ductwork occupying the same space. Some software packages now perform automatic interference checking. Layering features also help an HVAC designer coordinate designs with other disciplines. Mistakes in design can be corrected even before the drawings are plotted to eliminate costly field rework or, worse, at-fault litigation. For complex projects, interference software applications are available that assist in managing interferences throughout the building data model.

HVAC system models and associated data can be used by building owners and maintenance personnel for ongoing facilities management, strategic planning, and maintenance. For instance, an air-handling unit can be associated with a preventative maintenance schedule in a separate facility management application. Models are useful for computer-aided manufacturing such as duct construction. The 3D building data model can also aid in developing sections and details for building drawings. CAD programs can also automate cross-referencing of drawings, drawing notations, and building documents.

In addition to the concept of the single-building data model, the Internet is has greatly influenced engineering workflows. As bandwidth continues to widen, the speed of the Internet has allowed engineering firms to expand their clients, partners, and services worldwide. Software applications are available that allow users to design projects and share building model data globally over the Internet, and can be used for simple viewing and redlining as well. Project managers can view all aspects of the design process live and redline drawings simply by using a Web browser.

Computer Graphics and Modeling

Computer graphics programs may be used to create and manipulate pictorial information. Information can be assimilated more easily when presented as graphical displays, diagrams, and models. Historically, building scale models has improved the design engineer's understanding and analysis of early prototype designs. The psychrometric chart has also been invaluable to HVAC engineers for many years.

Combining alphanumerics (text) with computer graphics lets the design engineer quickly evaluate design alternatives. Computers can simulate design problems with three-dimensional color images that can predict the performance of mechanical systems before they are constructed. Simulation graphics software is also used to evaluate design conditions that cannot ordinarily be tested with scale models because of high costs or time constraints. Product manufacturability and economic feasibility may thus be determined without constructing a working prototype. Whereas historically only a few dozen scale-model tests could be performed before full-scale manufacturing, combined computer and scale-model testing allows hundreds or thousands of tests to be performed, improving reliability in product design. Graphic modeling and simulation of complex fluid flow fields are also used to simulate airflow fields in unidirectional cleanrooms, and may eventually make cleanroom mock-ups obsolete (Busnaina et al. 1988). Computer models of particle trajectories, transport mechanisms, and contamination propagation are also commercially available (Busnaina 1987).

Integrated CADD and expert systems can help the building designer and planner with construction design drawings and with construction simulation for planning and scheduling complex building construction scenarios (Potter 1987).

Architects use software that creates a 3D model of the building. **Building information modeling (BIM)** is a building design and documentation methodology that relies on the creation and collection of interrelated computable information about a building project so that reliable, coordinated, and internally consistent digital representations of the building are available for design decision making, production of high-quality construction documents, construction planning, and predicting performance in various ways.

A simple, helpful tool for the HVAC engineer is graphic representation of **thermodynamic properties and thermodynamic cycle analysis**. These programs may be as simple as computer-generated psychrometric charts with cross-hair cursor retrieval of properties and computer display magnification of chart areas for easier data retrieval. More complex software can graphically represent thermodynamic cyclic paths overlaid on two- or three-dimensional thermodynamic property graphs. With simultaneous graphic display of the calculated results of Carnot efficiency and COP, the user can understand more readily the cycle fundamentals and the practicality of the cycle synthesis (Abtahi et al. 1986).

Typical **piping and duct system simulation** software produces large amounts of data to be analyzed. Pictorially enhanced simulation output of piping system curves, pump curves, and load curves speeds the sizing and selection process. Hypothetical scenarios with numeric/graphic output increase the designer's understanding of the system and help avoid design problems that may otherwise become apparent only after installation (Chen 1988). Graphic-assisted fan and duct system design and analysis programs are also available (Mills 1989).

Airflow analysis of flow patterns and air streamlines is done by solving fundamental equations of fluid mechanics. Finite-element and finite-volume modeling techniques are used to produce two- or three-dimensional pictorial-assisted displays, with velocity vectors and velocity pressures at individual nodes solved and numerically displayed.

An example of pictorial output is Figure 5 in Chapter 16, where calculated airflow streamlines have been overlaid on a graphic of the cleanroom. With this display, the cleanroom designer can see potential problems in the configuration, such as the circular flow pattern in the lower left and right.

Major features and benefits associated with most computer flow models include the following:

- Two- or three-dimensional modeling of simple cleanroom configurations
- Modeling of both laminar and turbulent airflows
- CAD of air inlets and outlets of varying sizes and of room construction features
- Allowance for varying boundary conditions associated with walls, floors, and ceilings
- Pictorial display of aerodynamic effects of process equipment, workbenches, and people
- Prediction of specific airflow patterns in all or part of a cleanroom
- Reduced costs of design verification for new cleanrooms
- Graphical representation of flow streamlines and velocity vectors to assist in flow analysis

A graphical representation of simulated particle trajectories and propagation is shown in Figure 6 of Chapter 16. For this kind of graphic output, the user inputs a concentrated particle contamination and the program simulates the propagation of particle populations. In this example, the circles represent particle sources, and the diameter is a function of the concentration present. Such simulations help the cleanroom designer determine protective barrier placement.

Although research shows excellent correlation between flow modeling done by computer and in simple mock-ups, modeling software should not be considered a panacea for design; simulation of flow around complex shapes is still being developed, as are improved simulations of low-Reynolds-number flow.

Simulations range from two-dimensional and black and white to three-dimensional, color, and fully animated. Three-dimensional color outputs are often used not only for attractive presentations, but to increase user productivity (Mills 1989).

HVAC UTILITIES

Utility programs and modules are calculation tools that can be used both alone and integrated into other design tools.

Unit Conversion Programs

Many small utilities automatically convert between different sets of measurement units. Many of these are available as freeware or shareware. Chapter 38 of the 2005 *ASHRAE Handbook—Fundamentals* provides factors for unit conversions between SI and I-P units.

Psychrometric Utilities

Chapter 6 of the 2005 *ASHRAE Handbook—Fundamentals* provides equations to calculate psychrometric properties. Most of the utilities and Visual Basic® functions that are available to automate these calculations determine psychrometric properties from any two of the properties and a barometric pressure. Some also calculate entering and leaving properties from entering state-point(s) and a defined process (e.g., mixing of air streams, dehumidification), and plot to a psychrometric chart. Charting can be performed by scanning a psychrometric chart and determining the *x* and *y* axes by using the linear properties of dry-bulb temperature and humidity ratio.

Thermal Comfort Modules

An ASHRAE utility (ASHRAE 1997) calculates the predicted mean vote (PMV) for thermal comfort from the inputs for clothing, metabolic rate, mean radiant temperature, air speed, dry-bulb temperature, and relative humidity. This utility uses the calculations presented in ASHRAE *Standard* 55-1992.

Refrigeration Properties and Design

The program REFPROP (NIST; http://www.boulder.nist.gov/) allows the user to examine thermodynamic and transport properties for 39 pure refrigerants and blends. It may be used in an interactive mode. Because source code is included, it may also be used as part of a program that requires refrigerant properties. Other refrigerant property programs are also available from sources such as universities. Programs should be able to address the following refrigerant properties:

- Enthalpy
- Entropy
- Viscosity
- Thermal conductivity

Ventilation

Many ventilation programs are available to help designers meet the requirements of ASHRAE *Standard* 62, Ventilation for Acceptable Indoor Air Quality. As with any computer program, users should evaluate any program's technical capabilities, such as

- Ventilation requirements by application
- Application of the Multiple Space equation in *Standard* 62
- Use of ventilation effectiveness
- Application for spaces with intermittent or variable occupancy

In addition to technical capabilities, the units of input and output and the ability to interface with programs for input or output should also be examined.

SOURCES OF HVAC SOFTWARE

Many applications have been developed as the result of ASHRAE-funded research, ranging from database retrieval for use in HVAC&R calculations to demonstration versions of advanced tools.

The ASHRAE Web site (www.ashrae.org) and the ASHRAE Online Bookstore are good sources for obtaining this software, and provide information about these programs and their system requirements, as well as other sources of HVAC-related software.

INTEROPERABLE COMPUTER APPLICATIONS FOR THE HVAC&R INDUSTRY

HVAC&R computer applications have historically been stand-alone tools that require manual reentry of data to accomplish multi-disciplinary analysis. In most projects, these data must then be manually transcribed for use in other professional software, for work such as HVAC calculations and design, cost estimating, building energy performance simulation, and energy code compliance checking. This process requires time and resources. Furthermore, error detection and correction can be just as resource consuming; undetected errors can lead to serious problems. Any changes to the design require corresponding changes in transcription for other applications. Each data element in a building design may typically be independently recreated seven times in the course of design. Much of this information may be lost and/or outdated later in the building life cycle during construction, renovation, and facility maintenance.

The goal of automatically sharing data between different tools is becoming possible because of software interoperability, the ability to share the same information among software applications used by practitioners performing different industry tasks. National and international efforts to develop standardized data models that allow software interoperability are well under way. A key product of these efforts is the Industry Foundation Classes (IFC) data model developed by the International Alliance for Interoperability (IAI). Members of the IAI, such as ASHRAE, work to develop cross-platform and cross-application communication standards.

Interoperability also requires that software vendors incorporate standard data models in their software applications. As shown in Figure 3, this can be done either by directly accessing and updating an IFC data file or by indirect access through an IFC-compliant data server. Several CAD tools now have implementations based on the evolving IFC data model standard, allowing building geometry input in these tools to be easily shared with other IFC-compliant tools. Nongeometric building data (e.g., construction material properties, HVAC&R equipment characteristics) are also included in the IFC data model. In addition to CAD tools, many other IFC-based HVAC&R software applications are available. Current information on state-of-the-art software interoperability is available at the Web addresses listed in the Bibliography.

NETWORKING COMPONENTS

Computers use resources that are commonly arranged into networks comprised of hardware and software components. Hardware network components include the following:

- Hubs
- Switches

Fig. 3   Software Interoperability Based on IFC Data Model Standard

- Routers
- Bridges
- Repeaters

Software network components usually take one of two forms: (1) dynamic link libraries (DLLs) to control network hardware, or (2) applications to communicate between computers according to adopted networking standards (e.g., IEEE 802.3 Ethernet).

Numerous computer network configurations exist for intra-, inter-, and extra-office data communication. Some common examples include

- Local area networks (LANs)
- Wide area networks (WANs)
- Metropolitan area networks (MANs)
- Intranet
- Extranet
- Internet

Figure 4 is a diagram of large business system architecture with Internet connections. The system has a large number of personal computers connected via Ethernet to a central wiring closet device called a hub. This hub simplifies the wiring infrastructure by allowing centralized wiring termination for modular utility connections to individual computers. The firewall, a computer security barrier, protects against unauthorized access from the outside Internet to individual nodes inside the firewall. Users may connect to the Internet either through a corporate router or indirectly from home through an Internet service provider (ISP), which may charge a fee for the service. Higher-bandwidth connections typically cost more as speed increases.

LAN PROTOCOLS

The Ethernet protocol is the most widely used and accepted local area network (LAN) standard, and is used extensively in industry. Because of its pervasive acceptance in industry, HVAC building automation protocols such as BACnet® and LONWORKS® allow their protocols to use Ethernet in their physical layer. Ethernet is a multi-access, packet-switching network where each node can request access to the network on an equal basis with any other node. Ethernet uses the collision sense, multiple access/collision detect (CSMA/CD) technique: if two nodes transmit at the same time, a collision occurs; both nodes then wait a random period of time and try again. This allows efficient allocation of bandwidth based on need.

An Ethernet LAN can use different media, such as the following:

- 10Base5, also known as Thick Net, which uses the large coaxial cable RG-11
- 10Base2, also known as Thin Net, which uses the smaller coaxial cable RG-58
- Fiber-optic cable
- 10Base-T (Twisted Pair), the most popular type, which has a wiring limitation length of 100 ft and is typically used in centralized wiring systems. These cables typically use an RJ-45 connector.

A faster version of Ethernet, called 100Base-T or Fast Ethernet, supports data transfer rates of 100 Mbps; however, the fastest version, Gigabit Ethernet, supports data rates of 1000 Mbps (1 Gbps).

TRANSMISSION CONTROL PROTOCOL/ INTERNET PROTOCOL

Transmission control protocol/internet protocol (TCP/IP) is a set of protocols that allow computers to communicate with each other. TCP/IP is the language of the Internet, and is also used in local networks, intranets, and extranets. As communication protocols such as TCP/IP have gained acceptance, availability of components based on these protocols has increased and driven networking costs down.
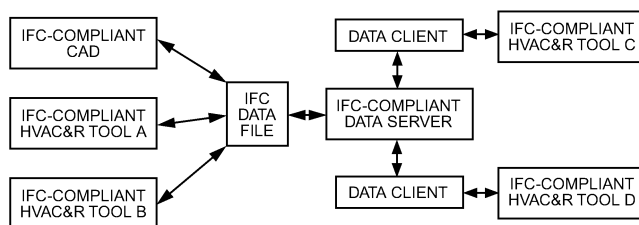
WIRELESS SERVICE

One of several immediately applicable new technologies is wireless connections for computers and equipment (e.g., to the Internet or to a LAN). Wireless communications to remote sensors can provide a low-cost solution where the cost of running conventional wiring is prohibitive or inappropriate.

Wireless monitoring components include a wireless transmitter and a Web site. The transmitter is mounted on or near the equipment being monitored. The Web site determines what alerts are sent to whom, and the method of delivery (e.g., e-mail, pager, telephone). Alert messages specify the condition that triggered the alert and the location, make, model, and serial number of the equipment. Also, field service technicians can inspect service procedures, service request, and maintenance from a remote computer at the job site to determine repair history on a piece of equipment.

Issues such as reliability, battery replacement alerts, maintenance, and reliability due to electromagnetic noise and interference should be considered when using wireless communications.

TELEPHONY STANDARDS

Regular analog phone service offers limited bandwidth and can support analog phone modems up to 56 kilobits per second (kbps). Digital phone standards include digital subscriber line (DSL), which can support bandwidth from 640 kbps to 3 Mbps but is limited to a 10,000 ft wire length from the telephone switching office. Cable modems provide high-speed access from traditional cable TV service companies. Cable networks generally have download speeds roughly between 500 kbps and 6 Mbps, but are often limited to about 768 kbps upload speed. Fiber-optic Internet connections are available in some areas, offering download bandwidth up to 30 Mbps and upload bandwidth up to 5 Mbps. As with DSL and cable modems, fiber-optic users may not have the maximum bandwidth available at all times. Note that, for most users, even the slowest bandwidth available from a DSL, cable, or fiber connection is sufficient. Higher bandwidth is very useful for users who frequently download music, video, or other large files from the Internet. In addition to the wired connection types, wireless connection standards with a range and bandwidth suitable to compete with DSL, cable, and fiber connections are being developed.

T1 and T3 are high-speed digital communication lines used by main communications trunks between servers, or for access to the Internet from an Internet service provider or company connection line. T1 connection speed is a maximum of 1.5 Mbps; T3 maximum speed is 44.736 Mbps. Asynchronous transfer mode (ATM) digital service provides high-speed communication at a typical maximum data rate of 155 Mbps.

FIREWALLS

Firewalls (computer security barriers), frequently used to prevent outside individuals from accessing internal, proprietary networked resources, can be designed to block certain messages from coming into or leaving the network. Firewalls are typically implemented in a high-speed router, and can efficiently block all communication to a specific IP address. All messages that enter and leave the intranet pass through the firewall, which examines each message and halts progress of illegal communications. Firewalls are an essential part of corporate computer security systems, and are also commonly implemented as software on a PC.

MONITORING AND CONTROL

A control system performs two primary functions: monitoring (also referred to as data acquisition or data gathering) and control (also referred to as device control). A control consists of a set of
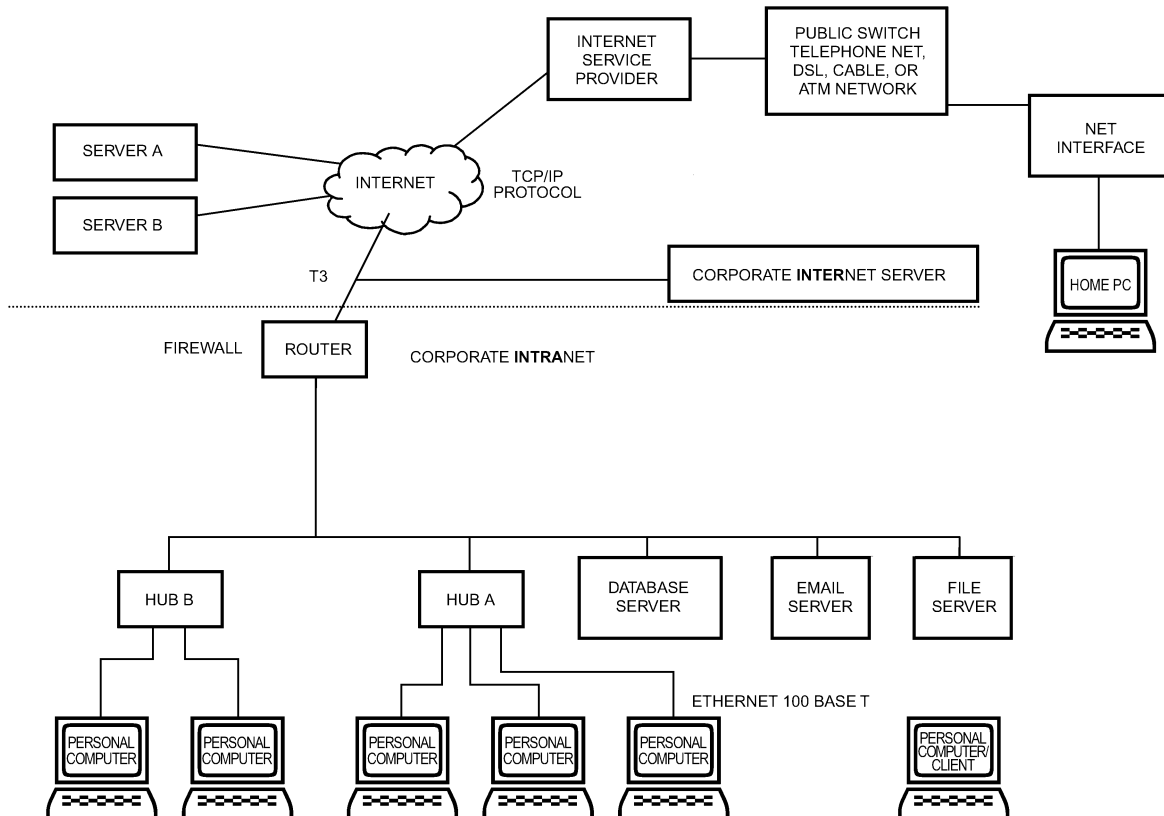
Fig. 4   **Example of Business System Architecture**

measured (monitored) parameters, a set of controlled parameters, and a control function that translates the measurement data into control signals applied to controlled parameters.

Supervisory control includes (1) **total system monitoring** (functions such as alarm reporting, energy measurement and calculation, logs, and trend reports) and (2) **overall control** (functions such as manual overrides, optimizing modification or discharge local loop set points, optimizing start-stop of subsystems, and controlled interaction between subsystems).

Types of supervisory control, depending on focus, include the following:

- Building automation system (BAS): automating monitoring and control
- Energy monitoring and control system (EMCS): conserving energy by both automatic and manual control with the aid of energy monitoring
- Energy management system (EMS): conserving energy by specific automatic control programs
- Facility management system (FMS): HVAC control of a subset of multiple subsystems or buildings, including fire, security, elevator, or manufacturing systems

BAS has become the most popular term for description of a computerized control system that may provide one or more of these functions.

INTEROPERABILITY

Standard communication protocols are developed in committee by professional societies, *open* protocols are created by manufacturers but available for all to use, and *proprietary* protocols are developed by manufacturers but not freely distributed. User needs should be determined before selecting a particular protocol for a given application.

There are two major standard protocols used in HVAC building automation today: BACnet® and LONWORKS®.

BACnet is the ASHRAE *Standard* 135 Building Automation and Control Networks Protocol. It provides mechanisms by which computerized equipment for a variety of building control functions may exchange information, regardless of the particular building service it performs. As a result, the BACnet protocol may be used by head-end computers, general-purpose direct digital controllers, and application-specific or unitary controllers. Working groups represented in BACnet include lighting, life safety and security, network security, utility integration, and XML applications.

BACnet is based on a four-layer collapsed architecture that corresponds to the physical, data link, network, and application layers of the ISO/OSI (International Standards Organization/Open Systems Interconnection) model. The application layer and a simple network layer are defined in the BACnet standard.

The **physical layer** provides a means of connecting devices and transmitting the electronic signals that convey the data. BACnet devices often use Ethernet networking, and can coexist with PCs on the same network.

The **data link layer** organizes the data into frames or packets, regulates access to the medium, provides addressing, and handles some error recovery and flow control.

Functions provided by the **network layer** include translation of global addresses to local addresses, routing messages through one or more networks, accommodating differences in network types and in the maximum message size permitted by those networks, sequencing, flow control, error control, and multiplexing. BACnet is designed so that there is only one logical path between devices, thus eliminating the need for optimal path routing algorithms.

The **presentation layer** provides a way for communicating partners to negotiate the transfer syntax used to conduct the communication. This transfer syntax is a translation from the abstract user view of data at the application layer to sequences of octets treated as data at the lower layers.

The **application layer** of the protocol provides the communication services required by the applications to perform their functions, in this case monitoring and control of the HVAC&R and other building functions.

LONWORKS defines a protocol for interoperability between control and automation devices. Task groups represented in LONMARK include HVAC, fire, industrial, lighting, vertical transportation (elevators), automated food service equipment, home/utility, network tools, refrigeration, router, security, semiconductor, sunblinds, system integration, and transportation.

Building automation system networks are local area networks, even though some applications must exchange information with devices in a building that is very far away. This long-distance communication is typically done through telephone networks. Using the Internet is becoming a popular, low-cost alternative to telephones.

DIRECT DIGITAL CONTROL (DDC) APPLICATIONS

Building management systems use standard workstation technology to connect or view system information. Standardization of building and vendor control protocol will allow future systems to access BACnet® and LONWORKS® systems. Although there are many approaches to communicating building information, the Web-browser-based client/server approach is becoming a standard interface.

Graphical representation of data from automation systems (e.g., operating conditions, trend data) is effective for enhancing operation and corrective action.

Direct digital control (DDC) allows precise and repeatable control using vendor hardware and software platforms. Many vendors allow access to DDC and set-point parameters, or are supporting common application standards such as distributed component object model (DCOM) ActiveX® and Enterprise JavaBeans®/common object request broker architecture (EJB/CORBA). Purchasing outside standards from companies specializing in certain components allows HVAC workstation providers to use common components for analysis, trending, and graphical presentation.

CONTROL COMPONENTIZATION

HVAC manufacturers use DDC microprocessors to create powerful, low-cost controls and feature-rich equipment. In the past, many of the control devices were proprietary and information was not shared between manufacturers. With standard communication protocols, diverse applications such as HVAC, energy, security, lighting, and fire controls in large buildings can use a single integrated control system.

Standard protocols allow application-specific component control systems designed for particular HVAC equipment to be included in building-wide strategies. For example, low-cost componentized DDCs provide operation, safety, maintenance, and even self-diagnostic information and control functions. Making a chiller or a variable-speed drive controller a part of a cohesive, building-wide control system is now possible because of standard protocols.

In the past, because all major HVAC equipment required some type of control system, control points were duplicated. Acceptance of communication standards has greatly reduced total control costs and increased functionality by providing information (e.g., part-load performance criteria) to users that was previously only available from manufacturer's testing.

As the functionality of component control increases and associated cost decreases, component-level interaction makes building-wide system integration less critical.

INTERNET-ENABLED
BUILDING AUTOMATION SYSTEMS

With Internet-enabled building automation systems, additional information outside the traditional control system (e.g., weather data, real-time energy data, pricing rates, manufacturers' equipment data) can be combined with real-time equipment data to create valuable analysis information. Commercial applications allow device integration to view real-time data, command equipment, and trend data. Users can manage energy consumption and costs, correct comfort problems, and solve equipment issues from distributed locations. Access control systems are available through the Internet using existing Internet standards such as TCP/IP and HTTP/XML.

CONVERGENCE OF INFORMATION SYSTEMS
AND INFORMATION TECHNOLOGY

As the information system (IS) and information technology (IT) industry has advanced, so have applications that can be used in building automation. Internet browser technology is a standard application, allowing information to be shared across nontraditional computer boundaries.

Because there is such demand in business for IT products, expertise and knowledge formerly reserved for IT applications can be applied to, for instance, user interface and building automation applications. A critical concern about integrating IT systems and building automation is information security. New security standards, such as the BACnet Network Security specification, should help address these concerns. Another common concern is that building automation systems will use a large amount of network bandwidth, but experience shows that bandwidth use by a properly configured system is not appreciable.

Web-based building controls that use the IT approach should create an open, interoperable structure for control automation systems. Implementing common field-bus standards and integration with Web browsers can be helpful for legacy system support. Rapid adoption of the Internet and standardization efforts in the field bus and building automation protocols have made developing a single standard for both Internet and control a goal for many vendors.

Combining building automation with Internet functionality will provide functionality in a user-friendly form.

INTERNET AND APPLICATIONS

The Internet originated in 1969 as an experimental project of the Advanced Research Project Agency (ARPA), and was called ARPANET. From its inception, the network was designed to be a decentralized, self-maintaining series of redundant links between computers and computer networks, capable of rapidly transmitting communications without direct human involvement or control, and with the automatic ability to reroute communications if one or more individual links were damaged or otherwise unavailable. Among other goals, this redundancy of linked computers was designed to allow vital research and communications to continue even if portions of the network were damaged by a war or other catastrophic event.

Messages between computers on the Internet do not necessarily travel entirely along the same path. The Internet uses packet-switching communication protocols that allow individual messages to be subdivided into smaller packets These are then sent independently to the destination and automatically reassembled by the receiving computer. Although all packets of a given message often travel along the same path to the destination, if computers along the route become overloaded, packets can be rerouted to less loaded computers.

No single entity—academic, corporate, governmental, or non-profit—administers the Internet. It exists and functions because hundreds of thousands of separate operators of computers and computer networks independently decided to use common data transfer protocols to exchange communications and information with other computers. No centralized storage location, control point, or communications channel exists for the Internet, and no single entity can control all of the information conveyed on the Internet.

Internet Communication Methods

The most common methods of communications on the Internet (as well as within the major on-line services) can be grouped into the following categories and are described in the following sections:

- One-to-one messaging (such as e-mail)
- One-to-many messaging (such as mailing list servers)
- Distributed message databases (such as USENET news groups)
- Real-time communication (such as Internet Relay Chat)
- Real-time remote computer use (such as Telnet)
- Remote information retrieval (such as ftp, gopher, and the World Wide Web)

Most of these methods of communication can be used to transmit text, data, computer programs, sound, visual images (i.e., pictures), and moving video images.

Servers

Network servers are fast becoming an important part of building automation and computer services systems. A Web page runs on a generic Web server. Files available for central storage and shared resources among users of a network are referred to as a file server. FTP servers allow users outside a company to store and manage large files such as drawing and construction documents. Mail servers are central storage servers that provide e-mail services to users. Database servers provide core database functionality, and can be added to application servers to access specific application services.

E-mail

Electronic mail (e-mail) is an extremely useful communications tool for use with local area networks, wide area networks, and the Internet. Using e-mail software, a message can be sent to individuals or to groups. Unlike postal mail, simple e-mail generally is not "sealed" or secure, and can be accessed or viewed on intermediate computers between the sender and recipient unless the message is encrypted. Modern e-mail software can attach graphics, executable programs, and other types of files. These features should be used with caution because of the large network resources required to support the file transfer.

Computer Viruses, Worms, and Trojan Horses. Computer viruses are programs that replicate themselves and typically do damage to the host system; they are frequently received through e-mail attachments. A **worm** is a self-contained program that spreads working copies of itself to other computer systems, typically through network connections. A **Trojan horse** is a program that performs undocumented activities not desired by the program user.

Antivirus software is vital to maintaining system security. Some PC operating systems are more vulnerable to viruses and worms than others.

Some newer e-mail programs automatically execute script files attached to e-mail; this leaves the user open to viruses and other types of attack. As a precaution, e-mail programs that automatically execute script files should not be used, or, if no other program is available, automatic script execution should be turned off. Only attachments from reputable or trusted sources should be opened, and then only after scanning the attachment with antivirus software.

Hoaxes. A common problem associated with e-mail is the hoax or chain letter. A hoax is commonly spread as a warning about serious consequences of a new virus, offers of free money or prizes, or dubious information about a person, product, or organization. A

common request from the hoax is to send it to everyone you know, in effect overloading the system with useless information. Although hoaxes and chain letters do not damage the host computer, they tax network resources, spread misinformation, and distract users from real work. Users should not pass hoaxes along, but should simply delete the message. Legitimate warnings about viruses come from IT staff or antivirus vendors. Individual hoaxes can be investigated through Web sites devoted to hoaxes and virus myths (e.g., Lawrence Livermore National Laboratory 2002).

Mailing Lists

The Internet also contains automatic mailing list services (e.g., LISTSERV) that allow communication about particular subjects of interest to a group of people. Users can subscribe to a mailing list on a particular topic of interest to them. The subscriber can submit messages on the topic to the mailing list server that are forwarded, either automatically or through a human moderator overseeing the list, to the e-mail accounts of all list subscribers. A recipient can reply to the message and have the reply also distributed to everyone on the mailing list. Most mailing lists automatically forward all incoming messages to all mailing list subscribers (i.e., they are unmoderated).

Distributed Message Databases

Distributed message databases, such as USENET newsgroups, are similar to mailing lists but differ in how communications are transmitted. User-sponsored newsgroups are among the most popular and widespread applications of Internet services, and cover all imaginable topics of interest. Like mailing lists, newsgroups are open discussions and exchanges on particular topics. Users, however, need not subscribe to the discussion mailing list in advance, but can access the database at any time. Some newsgroups are moderated, but most are open.

Real-Time Communication

Internet users can also engage in an immediate dialogue, in real time, with other people on the Internet, ranging from one-to-one communications to Internet Relay Chat (IRC), which allows two or more to type messages to each other that almost immediately appear on the receivers' computer screens. IRC is analogous to a telephone party line, using a computer and keyboard rather than a telephone. With IRC, however, at any one time there are thousands of different party lines available, with collectively tens of thousands of users discussing a huge range of subjects. Moreover, a user can create a new party line to discuss a different topic at any time. Some IRC conversations are moderated or have channel operators. Commercial online services often have their own chat systems to allow their members to converse.

Real-Time Remote Computer Use

Another method to access and control remote computers in real time is using Telnet, the main Internet protocol for connecting remote computers. For example, using Telnet, a researcher can use the computing power of a supercomputer located at a different university. A student can use Telnet to connect to a remote library to access the library's online catalog program.

Remote Information Retrieval

The most well-known use of the Internet is searching for and retrieving information located on remote computers. The three primary methods to locate and retrieve information on the Internet are ftp, Gopher, and HTTP (the World Wide Web).

A simple method, **file transfer protocol** (ftp) allows the user to transfer files between the local computer and a remote computer. The program and format named **Gopher** guides a search through the resources available on a remote computer.

World Wide Web. The World Wide Web (WWW) serves as the platform for a global, online store of knowledge, containing information from diverse sources and accessible to Internet users around the world. Though information on the Web is contained in individual computers, the fact that each of these computers is connected to the Internet allows all of the information to become part of a single body of knowledge. It is currently the most advanced information system developed on the Internet, and encompasses most information in previous networked information systems such as ftp, Gopher, wide-area information server (WAIS) protocol (used to search indexed databases on remote servers), and USENET.

Basic Operation. The WWW is a series of documents stored in different computers all over the Internet. An essential element of the Web is that each document has an address (rather like a telephone number).

Many organizations now have home pages on the Web, which, through links from the home page, guide the user to information about or relevant to that organization.

Links may also take the user from the original Web site to another Web site on another computer connected to the Internet. These links from one computer to another, from one document to another across the Internet, are what unify the Web into a single body of knowledge, and what makes the Web unique.

Publishing. The WWW allows people and organizations to communicate easily and quickly. Information is published on the Web; this process requires only a computer connected to the Internet and running WWW server software. The computer can be anything from an inexpensive personal computer to several state-of-the-art computers filling a small building. Many Web publishers choose instead to lease disk storage space from a company with the necessary facilities, eliminating the need to own any equipment.

Information to be published on the Web must be formatted according to Web standards, which ensure that all users who want to view the material will be able to do so.

Web page design can significantly affect user satisfaction. Web pages with content limited to one screen tend be easier to use than long Web pages that require scrolling. Web pages with large graphics files or that require special software to view the page may discourage low-bandwidth-connection users (e.g., internet access over regular analog phone lines) because of long waits. Maintaining and updating Web content is important: regular changes encourage repeat users. Web pages that give current information available nowhere else create value for users and encourage new and repeat visitors. However, care must be taken to obtain written permission for use of copyrighted material. Web sites can be open to all Internet users, or closed (creating an intranet), accessible only to those with advance authorization. Many publishers choose to keep their sites open to give their information the widest potential audience.

Searching the Web. Systems known as **search engines** allow users of the Web to search by category or by key words for particular information. The engine then searches the Web and presents a list linked to sites that contain the search term(s). Users can then follow individual links, browsing through the information on each site, until the desired material is found. There are also Web-based directories maintained by humans that can often give more precise results for a search in a particular area.

Search engines results can be narrowed by adding more key words: for example, a search for the word HVAC may end up with a list several hundred pages long, but a narrower search for HVAC VAV could narrow the focus.

Common Standards. The Web links disparate information on Internet-linked computers by using a common information storage format called **hypertext markup language (HTML)** and a common language for the exchange of Web documents, **hypertext transfer protocol (HTTP)**. HTML documents can contain text, images, sound, animation, moving video, and links to other resources.

Although the information itself may be in many different formats and stored on computers that are not otherwise compatible, these Web standards provide a basic set of standards that allow communication and exchange of information.

Many specialized programs exist to create and edit HTML files. Like HTML, **extensible markup language (XML)**, is a subset of the standard generalized markup language (SGML) protocol. XML applies the same document presentation principles of HTML to data interchange beyond simply displaying the data. XML separates data content from its presentation. This allows for different visual renditions of the same message, for displays on different devices.

Supervisory Groups. No single authority controls the entire Internet, but it is guided by the Internet Society (ISOC). ISOC is a voluntary membership organization intended to promote global information exchange through the Internet (Krol and Hoffman 1996). The Internet Architecture Board (IAB) defines Internet communication standards. The IAB also keeps track of information that must remain unique. For example, each computer on the Internet has a unique 32-bit address. The IAB does not actually assign the addresses, but it makes the rules about how to assign them (Krol and Hoffman 1996).

Collaborative Design

The Internet is revolutionizing how project teams collaborate. Interactions, such as sharing or jointly developing drawings or documents or designing software, can now take place efficiently with collaborators around the world.

Collaborative design raises many coordination issues. Methods of sharing data, such as distributed databases, revision and developmental accounting, and security concerns associated with the transmission of design information must be carefully considered.

SECURITY ISSUES

Computer security requires sound planning and continuous maintenance and monitoring. Mail servers can scan for viruses before users open e-mail, and individual virus software loaded on individual machines serves as a second layer of protection (see also the section on Computer Viruses, Worms, and Trojan Horses). Always save attached files to a safe directory and scan with antivirus software before using. Typically, IS and IT staff have a dedicated support person and strategy to maintain security.

A critical area for computer security is user names and passwords. Many systems require frequent changes of passwords with minimum length, number, case, and other requirements. Passwords should never be released to anyone.

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FURTHER INTERNET RESOURCES

BACnet Web site: www.bacnet.org
BACnet Manufacturers Association: www.bacnetassociation.org
FIATECH: www.fiatech.org
International Alliance for Interoperability: www.iai-international.org
LONMARK Interoperability Association: www.lonmark.org

CHAPTER 40

BUILDING ENERGY MONITORING

BUILDING energy monitoring provides realistic, empirical information from field data to enhance understanding of actual building energy performance and can help quantify changes in performance over time. Although different building energy monitoring projects can have different objectives and scopes, all have several issues in common that allow methodologies and procedures (monitoring protocols) to be standardized.

This chapter provides guidelines for developing building monitoring projects that provide the necessary measured data at acceptable cost. The intended audience comprises building owners, building energy monitoring practitioners, and data end users such as energy and energy service suppliers, energy end users, building system designers, public and private research organizations, utility program managers and evaluators, equipment manufacturers, and officials who regulate residential and commercial building energy systems.

Monitoring projects can be **uninstrumented** (i.e., no additional instrumentation beyond the utility meter) or **instrumented** (i.e., billing data supplemented by additional sources, such as an installed instrumentation package, portable data loggers, or building automation system). Uninstrumented approaches are generally simpler and less costly, but they can be subject to more uncertainty in interpretation, especially when changes made to the building represent a small fraction of total energy use. It is important to determine (1) the accuracy needed to meet objectives, (2) the type of monitoring needed to provide this accuracy, and (3) whether the desired accuracy justifies the cost of an instrumented approach.

Instrumented field monitoring projects generally involve a data acquisition system (DAS), which typically comprise various sensors and data-recording devices (e.g., data loggers) or a suitably equipped building automation system. Projects may involve a single building or hundreds of buildings and may be carried out over periods ranging from weeks to years. Most monitoring projects involve the following activities:

- Project planning
- Site installation and calibration of data acquisition equipment (if required)
- Ongoing data collection and verification
- Data analysis and reporting

These activities often require support by several professional disciplines (e.g., engineering, data analysis, management) and construction trades (e.g., electricians, controls technicians, pipe fitters).

Useful building energy performance data cover whole buildings, lighting, HVAC equipment, water heating, meter readings, utility demand and load factors, excess capacity, controller actuation, and building and component lifetimes. Current monitoring practices vary considerably. For example, a utility load research project may tend to characterize the average performance of buildings with relatively few data points per building, whereas a test of new technology performance may involve monitoring hundreds of parameters within a single facility. Monitoring projects range from broad research studies to very specific, contractually required savings verification carried out by performance contractors. However, all practitioners should use accepted standards of monitoring practices to communicate results. Key elements in this process are (1) classifying the types of project monitoring and (2) developing consensus on the purposes, approaches, and problems associated with each type (Haberl et al. 1990; Misuriello 1987). For example, energy savings from energy service performance contracts can be specified on either a whole-building or component basis. Monitoring requirements for each approach vary widely and must be carefully matched to the specific project. Procedures in ASHRAE *Guideline* 14-2002 and the IPMVP (2002) can be used to determine monitoring requirements.

REASONS FOR ENERGY MONITORING

Monitoring projects can be broadly categorized by their goals, objectives, experimental approach, level of monitoring detail, and uses (Table 1). Other factors, such as resources available, data validation and analysis procedures, duration and frequency of data collection, and instrumentation, are common to most, if not all, projects.

Energy End Use

Energy end-use projects typically focus on individual energy systems in a particular market sector or building type. Monitoring usually requires separate meters or data collection channels for each end use, and analysts must account for all factors that may affect energy use. Examples of this approach include detailed utility load research efforts, evaluation of utility incentive programs, and end-use calibration of computer simulations. Depending on the project objectives, the frequency of data collection may range from one-time measurements of full-load operation to continuous time-series measurements.

Specific Technology Assessment

Specific technology assessment projects monitor field performance of specific equipment or technologies that affect building energy use, such as envelope retrofit measures, major end-use system loads or savings from retrofits (e.g., lighting), or retrofits to or performance of mechanical equipment.

The typical goal of retrofit performance monitoring projects is to estimate savings resulting from the retrofit despite potentially significant variation in inside/outside conditions, building characteristics, and occupant behavior unrelated to the retrofit. The frequency and complexity of data collection depend on project objectives and site-specific conditions. Projects in this category assess variations in performance between different buildings or for the same building before and after the retrofit.

Field tests of end-use equipment are often characterized by detailed monitoring of all critical performance parameters and operational modes. In evaluating equipment performance or energy efficiency improvements, it is preferable to measure in situ performance. Although manufacturers' data and laboratory performance measurements can provide excellent data for sizing and selecting

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Table 1   Characteristics of Major Monitoring Project Types

Project Type	Goals and Objectives	General Approach	Level of Detail	Uses
Energy end use	Determine characteristics of specific energy end uses in building.	Often uses large, statistically designed sample. Monitor energy demand or use profile of each end use of interest.	Detailed data on end uses metered. Collect building and operating data that affect end use.	Load forecasting by end use. Identify and confirm energy conservation or demand-side management opportunities. Simulation calculations. Rate design.
Specific technology assessment	Measure field performance of building system technology or retrofit measure in individual buildings.	Characterize individual building or technology, occupant behavior, and operation. Account and correct for variations.	Uses detailed audit, submetering, inside temperature, on-site weather, and occupant surveys. May use weekly, hourly, or short-term data.	Technology evaluation. Retrofit performance. Validate models and predictions.
Energy savings measurement and verification	Estimate the impact of retrofit, commissioning, or other building alteration to serve as basis for payments or benefits calculation.	Preretrofit consumption is used to create baseline model. Post-retrofit consumption is measured; the difference between the two is savings.	Varies substantially, including verification of potential to provide savings, retrofit isolation, whole-building, or calibrated simulation.	Focused on specific campus, building, component, or system. Amount and frequency of data varies widely between projects.
Building operation and diagnostics	Solve problems. Measure physical or operating parameters that affect energy use or that are needed to model building or system performance.	Typically uses one-time and/or short-term measurement with special methods, such as infrared imaging, flue gas analysis, blower door, or coheating.	Focused on specific building component or system. Amount and frequency of data vary widely between projects.	Energy audit. Identify and solve operation and maintenance, inside air quality, or system problems. Provide input for models. Building commissioning.

equipment, installed performance can vary significantly from that at design conditions. The project scope may include reliability, maintenance, design, energy efficiency, sizing, and environmental effects (Phelan et al. 1997a, 1997b).

Savings Measurement and Verification (M&V)

Accountability is increasingly necessary in energy performance retrofits, whether they are performed as part of energy savings performance contracting (ESPC) or performed directly by the owner. In either case, savings measurement and verification (M&V) is an important part of the project. Because the actual energy savings cannot be measured directly, the appropriate role of energy monitoring methodology is to

- Ensure that appropriate data are available, including preretrofit data if retrofits are installed
- Accurately define baseline conditions and assumptions
- Confirm that proper equipment and systems were installed and have the potential to generate the predicted energy savings
- Take postretrofit measurements
- Estimate the energy savings achieved

Proper assessment of an energy retrofit involves comparing before and after energy use, and adjusting for all nonretrofit changes that affected energy use. Weather and occupancy are examples of factors that often change. To assess the effectiveness of the retrofit alone, the influence of these other complicating factors must be removed as best possible. Relationships must be found between energy use and these factors to remove the influence of the factors from the energy savings measurement. These relationships are usually determined through data analysis, not textbook equations. Because data analysis can be conducted in an infinite number of ways, there can be no absolute certainty about the relationship chosen. The need for certainty must be carefully balanced with measurement and analysis costs, recognizing that absolute certainty is not achievable. Among the numerous sources of uncertainty are instrumentation or measurement error, normalization or model error, sampling error, and errors of assumptions. Each source can be minimized to varying degrees by using more sophisticated measurement equipment, analysis methods, sample sizes, and assumptions. However, more certain savings determinations generally follow the law of diminishing returns, where further increases in certainty come at progressively greater expense. Total certainty is seldom achievable, and even less frequently cost-effective (ASHRAE *Guideline* 14).

Other resources are also available. One of the widest known is the *International Performance Measurement and Verification Protocol* (IPMVP 2002). The IPMVP is more general than ASHRAE *Guideline* 14 but provides important background for understanding the larger context of M&V efforts.

Building Diagnostics

Diagnostic projects measure physical and operating parameters that determine the energy use of buildings and systems. Usually, the project goal is to determine the cause of problems, model or improve energy performance of a building or building systems, or isolate effects of components. Diagnostic tests frequently involve one-time measurements or short-term monitoring. To give insight, the frequency of measurement must be several times faster than the rate of change of the effect being monitored. Some diagnostic tests require intermittent, ongoing data collection.

The most basic energy diagnostic for buildings is determining rate of energy use or power for a specific period, from essentially a single point in time to a few weeks. The scope of measurement may include the whole building or only one component. The purpose can range from measurement system parameter estimation to verification of nameplate information. Daily or weekly profiles may also be of interest.

A large number of diagnostic measurement procedures are used for energy measurements in residential buildings, particularly single-family. Typical measurements for single-family residences include (1) flue gas and other analysis procedures to determine steady-state furnace combustion efficiency and the efficiency of other end uses, such as air conditioners, refrigerators, and water heaters; (2) fan pressurization tests to measure and locate building envelope air leakage (ASTM *Standard* E779) and tests to measure airtightness of air distribution systems (Modera 1989; Robison and Lambert 1989); and (3) infrared thermography to locate thermal defects in the building envelope and other methods to determine overall building envelope parameters (Subbarao 1988).

Energy systems in multifamily buildings can be much more complex than those in single-family homes, but the types of diagnostics are similar: combustion equipment diagnostics, air leakage measurements, and infrared thermography to identify thermal defects or moisture problems (DeCicco et al. 1995). Some techniques are designed to determine the operating efficiency of steam and hot-water boilers and to measure air leakage between apartments.

Diagnostic techniques have been designed to measure the overall airtightness of office building envelopes and the thermal performance

of walls (Armstrong et al. 2001; Persily and Grot 1988; Sellers et al. 2004). Practicing engineers also use a host of monitoring techniques to aid in diagnostics and analysis of equipment energy performance. Portable data loggers are often used to collect time-synchronized distributed data, allowing multiple data sets (e.g., chiller performance and ambient conditions) to be collected and quickly analyzed. Similar short-term monitoring procedures are used to provide more detailed and complete commercial building system commissioning. Short-term, in situ tests have also been developed for pumps, fans, and chillers (Phelan et al. 1997a, 1997b).

Diagnostics are also well suited to support development and implementation of building energy management programs (see Chapter 35; Piette et al. 2000). Long-term diagnostic measurements have even supported energy improvements (Liu et al. 1994). Diagnostic measurement projects can generally be designed using procedures adapted to specific project requirements (see the section on Steps for Project Design and Implementation).

Equipment for diagnostic measurement may be installed temporarily or permanently to aid energy management efforts. Designers should consider providing permanent or portable check metering of major electrical loads in new building designs. Building automation systems also can be used to collect the data required for diagnostics. The same concept can be extended to fuel and thermal energy use.

PROTOCOLS FOR PERFORMANCE MONITORING

Examples of procedures (**protocols**) for evaluating energy savings for projects involving retrofit of existing building energy systems are presented here. These protocols should also be useful to those interested in more general building energy monitoring.

Building monitoring has been significantly simplified and made more professional in recent years by the development of fairly standardized monitoring protocols. Although there may be no way to define a protocol to encompass all types of monitoring applications, repeatable and understandable methods of measuring and verifying retrofit savings are needed. However, following a protocol does not replace adequate project planning and careful assessment of project objectives and constraints.

Residential Retrofit Monitoring

Protocols for residential building retrofit performance can answer specific questions associated with actual measured performance. For example, Ternes (1986) developed a single-family retrofit monitoring protocol, a data specification guideline that identifies important parameters to be measured. Both one-time and time-sequential data parameters are covered, and parameters are defined carefully to ensure consistency and comparability between experiments. Discrepancies between predicted and actual performance, as measured by the energy bill, are common. This protocol improves on billing data methods in two ways: (1) internal temperature is monitored, which eliminates a major unknown variable in data interpretation; and (2) data are taken more frequently than monthly, which potentially shortens monitoring duration. Utility bill analysis generally requires a full season of pre- and post-retrofit data. The single-family retrofit protocol may require only a single season.

Ternes (1986) identified both a minimum set of data, which must be collected in all field studies that use the protocol, and optional extensions to the minimum data set that can be used to study additional issues. See Table 2 for details. Szydlowski and Diamond (1989) developed a similar method for multifamily buildings.

The single-family retrofit monitoring protocol recommends a before/after experimental design, and the minimum data set allows performance to be measured on a normalized basis with weekly time-series data. (Some researchers recommend daily.) The protocol also allows hourly recording intervals for time-integrated parameters, an extension of the basic data requirements in the minimum data set. The minimum data set may also be extended

Table 2 Data Parameters for Residential Retrofit Monitoring

	Recording Period	
	Minimum	Optional
Basic Parameters		
House description		Once
Space-conditioning system description		Once
Entrance interview information		Once
Exit interview information		Once
Pre- and post-retrofit infiltration rates		Once
Metered space-conditioning system performance		Once
Retrofit installation quality verification		Once
Heating and cooling equipment energy consumption	Weekly	Hourly
Weather station climatic information	Weekly	Hourly
Indoor temperature	Weekly	Hourly
House gas or oil consumption	Weekly	Hourly
House electricity consumption	Weekly	Hourly
Wood heating use	—	Hourly
Domestic hot water energy consumption	Weekly	Hourly
Optional Parameters		
Occupant behavior		
Additional indoor temperatures	Weekly	Hourly
Heating thermostat set point	—	Hourly
Cooling thermostat set point	—	Hourly
Indoor humidity	Weekly	—
Microclimate		
Outdoor temperature	Weekly	Hourly
Solar radiation	Weekly	Hourly
Outdoor humidity	Weekly	Hourly
Wind speed	Weekly	Hourly
Wind direction	Weekly	Hourly
Shading		Once
Shielding		Once
Distribution system		
Evaluation of ductwork infiltration		Once

Source: Ternes (1986).

through optional data parameter sets for users seeking more information.

Data parameters in this protocol have been grouped into four data sets: basic, occupant behavior, microclimate, and distribution system (Table 2). The minimum data set consists of a weekly option of the basic data parameter set. Time-sequential measurements are monitored continuously during the field study. These are all time-integrated parameters (i.e., appropriate average values of a parameter over the recording period, rather than instantaneous values).

This protocol also addresses instrumentation installation, accuracy, and measurement frequency and expected ranges for all time-sequential parameters (Table 3). The minimum data set (weekly option of the basic data) must always be collected. At the user's discretion, hourly data may be collected, which allows two optional parameters to be monitored. Parameters from the optional data sets may be chosen, or other data not described in the protocol added, to arrive at the final data set.

This protocol standardizes experimental design and data collection specifications, enabling independent researchers to compare project results more readily. Moreover, including both minimum and optional data sets and two recording intervals accommodates projects of varying financial resources.

Commercial Retrofit Monitoring

Several related guidelines have been created for the particular application of retrofit savings (M&V). ASHRAE *Guideline* 14 provides methods for effectively and reliably measuring the energy and demand savings due to building energy projects. The guideline

Table 3   Time-Sequential Parameters for Residential Retrofit Monitoring

Data Parameter	Accuracy[a]	Range	Stored Value per Recording Period	Scan Rate[b] Option 1	Option 2
Basic Parameters					
Heating/cooling equipment energy consumption	3%		Total consumption	15 s	15 s
Indoor temperature	1.0°F	50 to 95°F	Average temperature	1 h	1 min
House gas or oil consumption	3%		Total consumption	15 s	15 s
House electricity consumption	3%		Total consumption	15 s	15 s
Wood heating use	1.0°F	50 to 800°F	Average surface temperature or total use time		1 min
Domestic hot water	3%		Total consumption	15 s	15 s
Optional Data Parameter Sets					
Occupant behavior					
Additional indoor temperatures	1.0°F	50 to 95°F	Average temperature	1 h	1 min
Heating thermostat set point	1.0°F	50 to 95°F	Average set point		1 min
Cooling thermostat set point	1.0°F	50 to 95°F	Average set point		1 min
Indoor humidity	5% rh	10 to 95% rh	Average humidity	1 h	
Microclimate					
Outdoor temperature	1.0°F	−40 to 120°F	Average temperature	1 h	1 min
Solar radiation	10 Btu/h·ft^2	0 to 350 Btu/h·ft^2	Total horizontal radiation	1 min	1 min
Outdoor humidity	5% rh	10 to 95% rh	Average humidity	1 h	1 min
Wind speed	0.5 mph	0 to 20 mph	Average speed	1 min	1 min
Wind direction	5°	0 to 360°	Average direction	1 min	1 min

Source: Ternes (1986).   [a]All accuracies are stated values.   [b]Applicable scan rates if nonintegrating instrumentation is used.

Table 4   Performance Data Requirements of Commercial Retrofit Protocol

Projects with Submetering		
	Before Retrofit	**After Retrofit**
Utility billing data (for each fuel)	12 month minimum	3 month minimum (12 months if weather normalization required)
Submetered data (for all recording intervals)	All data for each major end use, up to 12 months	All data for each major end use, up to 12 months
	Type	**Recording Interval**	**Period Length**
Temperature data (daily maximum and minimum must be provided for any periods without integrated averages)	Maximum and minimum —or— Integrated averages	Daily —or— Same as for submetered data but not longer than daily	Same as billing data length —or— Length of submetering
Projects Without Submetering		
	Before Retrofit	**After Retrofit**
Utility billing data (for each fuel)	12 month minimum	12 month minimum
	Type	**Recording Interval**	**Period Length**
Temperature data	Maximum and minimum —or— Integrated averages	Daily	Same as billing data length

defines a minimum acceptable level of performance in measuring energy and demand savings from energy conservation measures in residential, commercial, or industrial buildings. These measurements can serve as the basis for commercial transactions between energy services providers and customers who rely on measured energy savings as the basis for financing payments. Three approaches are discussed: whole building, retrofit isolation, and calibrated simulation. The guideline includes an extensive resource on physical measurement, uncertainty, and regression techniques. Example M&V plans are also provided.

The *International Performance Measurement and Verification Protocol* (IPMVP 2002) provides guidance to buyers, sellers, and financiers of energy projects on quantifying energy savings performance of energy retrofits. The Federal Energy Management Program has produced guidelines specific to federal projects, which include many procedures usable for calculating retrofit savings in nonfederal buildings (Schiller Associates 2000).

On a more detailed level, ASHRAE Research Project RP-827 resulted in separate guidelines for in situ testing of chillers, fans, and pumps to evaluate installed energy efficiency (Phelan et al. 1997a, 1997b). The guidelines specify the physical characteristics to be measured; number, range, and accuracy of data points required;

methods of artificial loading; and calculation equations with a rigorous uncertainty analysis.

In addition to these specialized protocols for particular monitoring applications, a number of specific laboratory and field measurement standards exist (see Chapter 56), and many monitoring source books are in circulation.

Finally, MacDonald et al. (1989) developed a protocol for field monitoring studies of energy improvements (retrofits) for commercial buildings. Similar to the residential protocol, it addresses data requirements for monitoring studies. Commercial buildings are more complex, with a diverse array of potential efficiency improvements. Consequently, the approach to specifying measurement procedures, describing buildings, and determining the range of analysis must differ.

The strategy used for this protocol is to specify data requirements, analysis, performance data with optional extensions, and a building core data set that describes the field performance of efficiency improvements. This protocol requires a description of the approach used for analyzing building energy performance. The necessary performance data, including identification of a minimum data set, are outlined in Table 4.

Commercial New Construction Monitoring

New building construction offers the potential for monitoring building subsystem energy consumption at a reasonable cost. Information obtained by monitoring operating hours or direct energy consumption can benefit building owners and managers by

- Verifying design intent
- Alerting them to inefficient or improper operation of equipment
- Providing data that can be useful in determining benefits of alternative operating strategies or replacement equipment
- Evaluating costs of operation for extending occupancy hours for special conditions or event
- Demonstrating effects of poor maintenance or identifying when maintenance procedures are not followed
- Diagnosing and fixing comfort and other space condition problems
- Diagnosing power quality problems
- Submetering tenants
- Verifying/improving savings of a performance contract
- Maintaining persistence of energy savings

To provide data necessary to improve building systems operation, monitoring should be considered for boilers, chillers, cooling towers, heat pumps, air-handling unit fans, large fan-coil units, major exhaust fans, major pumps, comfort cooling compressors, lighting panels, electric heaters, receptacle panels, substations, motor control centers, major feeders, service water heaters, process loads, and computer rooms.

Guidance on energy monitoring to determine energy savings for new construction design modifications is available in IPMVP (2003).

Construction documents may include provisions for various meters to monitor equipment and system operation. Some equipment can be specified to have factory-installed hour meters that record actual operating hours of the equipment. Hour meters can also be easily field-installed on any electrical motor.

More sophisticated power-monitoring systems, with electrical switchgear, substations, switchboards, and motor control centers, can be specified. These systems can monitor energy demand, energy consumption, power factor, neutral current, etc., and can be linked to a computer. These same systems can be installed on circuits to existing or retrofit fans, chillers, lighting panels, etc. Some equipment commonly used for improving system efficiency, such as variable-frequency drives, can be provided with capability to monitor kilowatt output, kilowatt-hours consumed, and other variables.

Using direct digital control (DDC) or building automation systems for monitoring is particularly appropriate in new construction. These systems can monitor, calculate, and record system status, water use, energy use at the main meter or of particular end-use systems, demand, and hours of operation, as well as start and stop building systems, control lighting, and print alarms when systems do not operate within specified limits. Initial specification of the new control system should include specific requirements for sensors, calculations, and trend logging and reporting functions. Special issues related to sensors and monitoring approaches can be found in Piette et al. (2000).

COMMON MONITORING ISSUES

Field monitoring projects require effective management of various professional skills. Project staff must understand the building systems being examined, quality control of data, data management, data acquisition, and sensor technology. In addition to data collection, processing, and analysis, the logistics of field monitoring projects require coordinating equipment procurement, delivery, and installation.

Key issues include the **accuracy** and **reliability** of collected data. Projects have been compromised by inaccurate or missing data, which could have been avoided by periodic sensor calibration and ongoing data verification.

Planning

Many common problems in monitoring projects can be avoided by effective and comprehensive planning.

Project Goals. Project goals and data requirements should be established before hardware is selected. Unfortunately, projects are often driven by hardware selection rather than by project objectives, either because monitoring hardware must be ordered several months before data collection begins or because project initiation procedures are lacking. As a result, the hardware may be inappropriate for the particular monitoring task, or critical data points may be overlooked.

Project Costs and Resources. After goal setting, the feasibility of the anticipated project should be reviewed in light of available resources. Projects to which significant resources can be devoted usually involve different approaches from those with more limited resources. This issue should be addressed early on and reviewed throughout the course of the project. Although it is difficult at this early stage to assess with certainty the cost of an anticipated project, rough estimates can be quite helpful.

Data Products. It is important to establish the type and format of the final results calculated from data before selecting data points. Failure to plan these data products first may lead to failure to answer critical questions.

Data Management. Failure to anticipate the typically large amounts of data collected can lead to major difficulties. The computer and personnel resources needed to verify, retrieve, analyze, and archive data can be estimated based on experience with previous projects.

Data Quality Control. It is also important to check and validate the quality and reasonableness of data before use. Failure to use some type of quality control typically results in data errors and invalid results.

Commitment. Many projects require long-term commitment of personnel and resources. Project success depends on long-term, daily attention to detail and on staff continuity.

Accuracy Requirements. The required accuracy of data products and accuracy of the final data and experimental design needed to meet these requirements should be determined early on. After the required accuracy is specified, the sample size (number of buildings, control buildings, or pieces of equipment) must be chosen, and the required measurement precision (including error propagation into final data products) must be determined. Because tradeoffs must usually be made between cost and accuracy, this process is often iterative. It is further complicated by a large number of independent variables (e.g., occupants, operating modes) and the stochastic nature of many variables (e.g., weather).

Advice. Expert advice should be sought from others who have experience with the type of monitoring envisioned.

Implementation and Data Management

The following steps can facilitate smooth project implementation and data management:

- Calibrate sensors before installation. Spot-check calibration on site. During long-term monitoring projects, recalibrate sensors periodically. Appropriate procedures and standards should be used in all calibration procedures [see ASHRAE *Guideline* 14 and IPMVP (2002)].
- Track sensor performance regularly. Quick detection of sensor failure or calibration problems is essential. Ideally, this should be an automated or a daily task. The value of data is high because they may be difficult or impossible to reconstruct.
- Generate and review data on a timely, periodic basis. Problems that often occur in developing final data products include missing

data from failed sensors, data points not installed because of planning oversights, and anomalous data for which there are no explanatory records. If data products are specified as part of general project planning and produced periodically, production problems can be identified and resolved as they occur. Automating the process of checking data reliability and accuracy can be invaluable in keeping the project on track and in preventing sensor failure and data loss.

Data Analysis and Reporting

For most projects, the collected data must be analyzed and put into reports. Because the objective of the project is to translate these data into information and ultimately into knowledge and action, the importance of this step cannot be overemphasized. Clear, convenient, and informative formats should be devised in the planning stages and adhered to throughout the project.

Close attention must be paid to resource allocation to ensure that adequate resources are dedicated to verification, management, and analysis of data and to ongoing maintenance of monitoring equipment. As a quality control procedure and to make data analysis more manageable, these activities should be ongoing. Data analysis should be carefully defined before the project begins.

STEPS FOR PROJECT DESIGN AND IMPLEMENTATION

This section describes methodology for designing effective field monitoring projects that meet desired goals with available project resources. The task components and relationships among the nine activities constituting this methodology are identified in Figure 1. The activities fall into four categories: project management, project development, resolution and feedback, and production quality and data transfer. Field monitoring projects vary in terms of resources, goals and objectives, data product requirements, and other variables, affecting how methodology should be applied. Nonetheless, the methodology provides a proper framework for advance planning, which helps minimize or prevent implementation problems.

An iterative approach to planning activities is best. The scope, accuracy, and techniques can be adjusted based on cost estimates and resource assessments. The initial design should be performed simply and quickly to estimate cost and evaluate resources. If costs are out of line with resources, adjustments are needed, such as when

desired levels of instrumentation exceed the resources available for the project. Planning should identify and resolve any tradeoffs necessary to execute the project within a given budget. Examples include reducing the scope of the project versus relaxing instrumentation specifications or accuracy requirements. These decisions often depend on what questions the project must answer and which questions can be eliminated, simplified, or narrowed.

One frequent oversight in project planning is failing to reserve sufficient time and resources for later analysis and reporting of data. Unanticipated additional costs associated with data collection and problem resolution should not jeopardize these resources.

Documenting the results of project planning should cover all nine parts of the process. This report can be a useful part of an overall project plan that may document other important project information, such as resources to be used, schedule, etc.

Part One: Identify Project Objectives, Resources, and Constraints

Start with a clear understanding of the decision to be made or action to be taken as a result of the project. The goals and objectives statement determines the overall direction and scope of the data collection and analysis effort. The statement should also list questions to be answered by empirical data, noting the error or uncertainty associated with the desired result. Realistic assessment of error is needed because requiring too small an uncertainty leads to an overly complex and expensive project. It is important in monitoring projects that a data acquisition plan be developed and followed with a clear idea of the **research questions** to be answered.

Resource requirements for equipment, personnel, and other items must feed into budget estimates to determine expected funding needed for different project objectives. Scheduling requirements must also be considered, and any project constraints defined and considered. Tradeoffs on budget and objectives require that priorities be established.

Even if a project is not research-oriented, it is attempting to obtain information, which can be stated in the form of questions. Research questions can have varying scopes and levels of detail, addressing entire systems or specific components. Some examples of research questions follow:

- Measurement and verification: Have contractors fulfilled their responsibilities of installing equipment and improving systems to achieve the agreed-upon energy savings?
- Classes of buildings: To an accuracy of 20%, how much energy has been saved by using a building construction/performance standard mandated in the jurisdiction?
- Particular buildings: Has a lapse in building maintenance caused energy performance to degrade?
- Particular components: What is the average reduction in demand charges during summer peak periods because of the installation of an ice storage system in this building?

Research questions vary widely in technical complexity, generally taking one of the following three forms:

- How does the building/component perform?
- Why does the building/component perform as it does?
- Which building/component should be targeted to achieve optimal cost-effectiveness?

The first form of question can sometimes be answered generically for a class of typical buildings without detailed monitoring and analysis, although detailed planning and thorough analysis are still required. The second and third forms usually require detailed monitoring and analysis and, thus, detailed planning.

In general, more detailed and precise goal statements are better. They ensure that the project is constrained in scope and developed to meet specific accuracy and reliability requirements. Usually, projects attempt to answer more than one research question, and
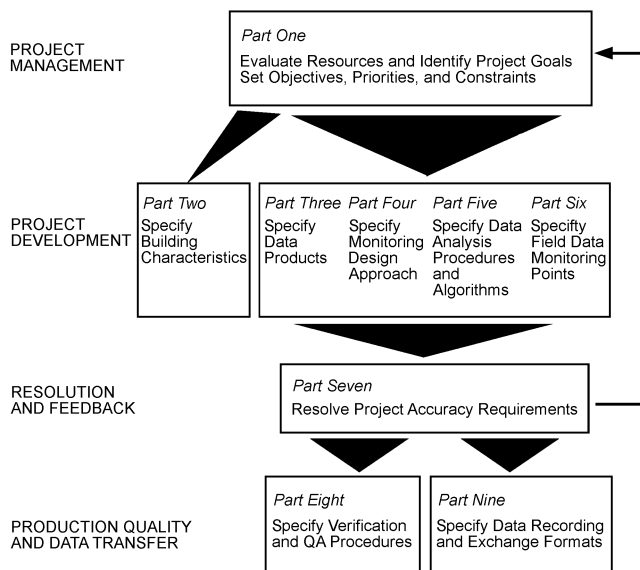
Fig. 1   Methodology for Designing Field Monitoring Projects

often consider both primary and secondary questions. All data collected should have a purpose of helping to answer a project question; the more specific the questions, the easier identifying required data becomes.

Part Two: Specify Building and Occupant Characteristics

Measured energy data will not be meaningful later to people who were not involved in the project unless the characteristics of the building being monitored and its use have been documented. To meet this need, a data structure (e.g., a characteristic database) can be developed to describe the buildings.

Building characteristics can be collected at many levels of detail, depending on the type of monitoring project and the parameters that affect results. For projects that determine whole-building performance, it is important to provide at least enough detail to document the following:

- General building type, use, configuration, and envelope (particularly energy-related aspects)
- Building occupant information (number, occupancy schedule, activities)
- Internal loads
- HVAC system descriptive information characterizing key parameters affecting HVAC system performance
- Type and quantity of other energy-using systems
- Any building changes that occur during the monitoring project
- Entrance interview information focusing on energy-related behavior of building occupants before monitoring
- Exit interview information documenting physical or lifestyle changes at the test site that may affect data analysis

The minimum level of detail is known as **summary characteristics** data. **Simulation-level characteristics** (detailed information collected for hourly simulation model input) may be desirable for some buildings. Regardless of the level of detail, the data should provide a context for analysts, who may not be familiar with the project, to understand the building and its energy use.

Part Three: Specify Data Products and Project Output

The objective of a monitoring project is typically not to produce data, but to answer a question. However, the data must be of high quality and must be presented to key decision makers and analysts in a convenient, informative format. The specific **data products** (format and content of data needed to meet project goals and objectives) must be identified and evaluated for feasibility and usefulness in answering project questions identified in Part One. Final data products must be clearly specified, together with the minimum acceptable data requirements for the project. It is important to clearly define an **analysis path** showing what will be calculated and what data are necessary to achieve desired results. Clear communication is critical to ensure that project requirements are satisfied and factors contributing to monitoring costs are understood.

Evaluation results can be presented in many forms, often as interim and final reports (possibly by heating and/or cooling season), technical notes, or technical papers. These documents must convey specific results of the field monitoring clearly and concisely. They should also contain estimates of the accuracy of the results.

The composition of data presentations and analysis summaries should be determined early to ensure that all critical parameters are identified (Hough et al. 1987). For instance, mock-ups of data tables, charts, and graphs can be used to identify requirements. Previously reported results can be used to provide examples of useful output. Data products should also be prioritized to accommodate possible cost tradeoffs or revisions resulting from other steps in the process such as error analysis (see Part Seven).

Although requirements for the minimum acceptable data results can often be specified during planning, data analysis typically reveals further requirements. Thus, budget plans should include allowances and optional data product specifications to handle additional or unique project output requirements uncovered during data analysis.

Longer-term goals and future information needs should be anticipated and explained to project personnel. For example, a project may have short- and long-term data needs (e.g., demonstrating reductions in peak electrical demand versus demonstrating cost-effectiveness or reliability to a target audience). Initial results on demand reduction may not be the ultimate goal, but rather a step toward later presentations on cost reductions achieved. Thus, it is prudent to consider long-term and potential future data needs so that additional supporting information, such as photographs or testimonials, may be identified and obtained.

Part Four: Specify Monitoring Design Approach

A general monitoring design must be developed that defines three interacting factors: the number of buildings in the study, the monitoring approach (or experimental design), and the level of detail in the data being measured. A less detailed or precise approach can be considered if the number of buildings is increased, and vice versa. If the goal is related to a specific product, the monitoring design must isolate the effects of that product. Haberl et al. (1990) discuss monitoring designs. For example, for retrofit M&V, protocols have been written allowing a range of different monitoring methods, from retrofit verification to retrofit isolation (ASHRAE *Guideline* 14; IPMVP 2002; Schiller Associates 2000). Some monitoring approaches are more suited than others to larger numbers of buildings.

Specifying the monitoring design approach is particularly important because total building performance is a complex function of several variables, changes in which are difficult to monitor and to translate into performance. Unless care is taken with measurement organization and accuracy, uncertainties, errors (noise), and other variations, such as weather, can make it difficult to detect performance changes of less than 20% (Fracastoro and Lyberg 1983).

In some cases, judgment may be required in selecting the number of buildings involved in the project. If an owner seeks information about a particular building, the choice is simple: the number of buildings in the experiment is fixed at one. However, for other monitoring applications, such as drawing conclusions about effects in a sample population of buildings, some choice is involved. Generally, error in the derived conclusions decreases as the square root of the number of buildings increases (Box 1978). A specific project may be directed at

- Fewer buildings or systems with more detailed measurements
- Many buildings or systems with less detailed measurements
- Many buildings or systems with more detailed measurements

For projects of the first type, accuracy requirements are usually resolved initially by determining expected variations of measured quantities (dependent variables) about their average values in response to expected variations of independent variables. For buildings, a typical concern is the response of heating and cooling loads to changes in temperature or other weather variables. The response of building lighting energy use to daylighting is another example of the relationship between dependent and independent variables. Fluctuations in response are caused by (1) outside influences not quantified by measured energy use data and (2) limitations and uncertainties associated with measurement equipment and procedures. Thus, accuracy must often be determined using statistical methods to describe mean tendencies of dependent variables.

For projects of the second and third types, the increased number of buildings improves confidence in the mean tendencies of the dependent response(s) of interest. Larger sample sizes are also needed for experimental designs with control groups, which are used

to adjust for some outside influences. For more information, see Box (1978), Fracastoro and Lyberg (1983), and Hirst and Reed (1991). Projects can also use more complex, multilevel measurement and modeling approaches to handle an array of technologies or help improve confidence in results (Hughes and Shonder 1998).

Most monitoring procedures use one or more of the following general experimental approaches:

On/Off. If the retrofit or product can be activated or deactivated at will, energy consumption can be measured in a number of repeated on/off cycles. On-period consumption is then compared to off-period consumption (Cohen et al. 1987; Woller 1989).

Before/After. Building, system, or component energy consumption is monitored before and after a new component or retrofit improvement is installed. Changes in factors not related to the retrofit, such as the weather and building operation during the two periods, must be accounted for, often requiring a model-based analysis (Fels 1986; Hirst et al. 1983; Kissock et al. 1992; Robison and Lambert 1989; Sharp and MacDonald 1990). This experimental design is the primary concern of most current building energy monitoring documents (ASHRAE *Guideline* 14; IPMVP 2002; Schiller Associates 2000).

Test/Reference. The building energy consumption data of two "identical" buildings, one with the product or retrofit being investigated, are compared. Because buildings cannot be absolutely identical (e.g., different air leakage distributions, insulation effectiveness, temperature settings, and solar exposure), measurements should be taken before installation as well, to allow calibration. Once the product or retrofit is installed, any deviation from the calibration relationship can be attributed to the product or retrofit (Fracastoro and Lyberg 1983; Levins and Karnitz 1986).

Simulated Occupancy. In some cases, the desire to reduce noise can lead the experimenter to postulate certain standard profiles for temperature set points, internal gains, moisture release, or window manipulation and to introduce this profile into the building by computer-controlled devices. The reference is often given by the test/reference design. In this case, both occupant and weather variations are nearly eliminated in the comparison (Levins and Karnitz 1986).

Nonexperimental Reference. A reference for assessing the performance of a building can be derived nonexperimentally using (1) a normalized, stratified performance database, such as energy use per unit area classified by building type (MacDonald and

Wasserman 1989) or (2) a reasonable standard building, simulated by a calculated hourly or bin-method calibrated building energy performance model subject to the same weather, equipment type, and occupancy as the monitored building.

This design, also called **calibrated simulation**, is a secondary concern of current building energy monitoring documents (ASHRAE *Guideline* 14; IPMVP 2002; Schiller Associates 2000).

Engineering Field Test. When an experiment focuses on testing a particular piece of equipment, actual performance in a building is often of interest. The building provides a realistic environment for testing the equipment for reliability, maintenance requirements, and comfort and noise levels, as well as energy usage. Energy consumption of mechanical equipment is significantly affected by the system control strategy. Testing procedures related to determining energy impacts should be designed to incorporate the control strategy of the equipment and its system (Phelan et al. 1997a, 1997b). This type of monitoring and testing can also be used to calibrate computer simulation models of as-built and as-operated buildings, which can then be used to evaluate whole-building energy consumption. The equipment may be extensively instrumented.

Some of the general advantages and disadvantages of these approaches are listed in Table 5 (Fracastoro and Lyberg 1983). Monitoring design choices have been successfully combined (e.g., the before/after and test/reference approaches). Questions to be considered in choosing a monitoring approach include the following:

- Can the building alteration being investigated be turned on and off at will? The on/off design offers considerable advantages.
- Are occupancy and occupant behavior critical? Changes in building tenants, use schedules, internal gains, temperature set points, and natural or forced ventilation practices should be considered because any one of these variables can ruin an experiment if it is not constant or accounted for.
- Are actual baseline energy performance data critical? In before/after designs, time must be allotted to characterize the before case as precisely as the after case. For instances in which heating and cooling systems are evaluated, data may be required for a wide range of anticipated ambient conditions.
- Is it a test of an individual technology, or are multiple technologies installed as a package being tested? If the effects of individual technologies are sought, detailed component data and careful model-based analyses are required.

Table 5 Advantages and Disadvantages of Common Experimental Approaches

Mode	Advantages	Disadvantages
Before/after	No reference building required. Same occupants implies smaller occupant variations. Modeling processes are mostly identical before/after.	Weather different before/after. More than one heating/cooling season may be needed. Model is required to account for weather and other changes.
Test/reference	One season of data may be adequate. Small climate difference between buildings.	Reference building required. Calibration phase required (may extend testing to two seasons). Occupants in either or both buildings can change behavior.
On/off	No reference building required. One season may be adequate. Modeling processes are mostly identical before/after. Most occupancy changes are small.	Requires reversible product. Cycle may be too long if time constants are large. Model is required to account for weather differences in cycles. Dynamic model accounting for transients may be needed.
Simulated occupancy	Noise from occupancy is eliminated. A variety of standard schedules can be studied.	Not "real" occupants. Expensive apparatus required. Extra cost of keeping building unoccupied.
Nonexperimental reference	Cost of actual reference building eliminated. With simulation, weather variation is eliminated.	Database may be lacking in strata entries. Simulation errors and definition of reference problematic. With database, weather changes usually not possible.
Engineering field test	Information focused on product of interest. Minimal number of buildings required. Same occupants during test.	Extensive instrumentation of product processes required. Models required to extrapolate to other buildings and climates. Occupancy effects not determined.

Source: Partially based on Fracastoro and Lyberg (1983).

- Does the technology have a single mode or multiple modes of operation? Can the modes be controlled to suit the experiment? If many modes are involved, it is necessary to test over a variety of conditions and conduct model-based analysis (Phelan et al. 1997a, 1997b).

Part Five: Specify Data Analysis Procedures and Algorithms

Data are useless unless they are distilled into meaningful products that allow conclusions to be drawn. Too often, data are collected and never analyzed. This planning step focuses on specifying the minimum acceptable data analysis procedures and algorithms and detailing how collected data will be processed to produce desired data products. In this step, monitoring practitioners should do the following:

- Determine the independent variables and analysis constants to be measured in the field (e.g., fan power, lighting and receptacle power, inside air temperature).
- Develop engineering calculations and equations (algorithms) necessary to convert field data to end products. This may include use of statistical methods and simulation modeling.
- Specify detailed items, such as the frequency of data collection, the required range of independent variables to be captured in the data set, and the reasons certain data must be obtained at different intervals. For example, 15 min interval demand data are assembled into hourly data streams to match utility billing data.

Determine proper NIST-traceable calibration standards for each sensor type to be used. For details, see the references in ASHRAE *Guideline* 14 and IPMVP (2002) for specific types of sensors. However, it is often impractical to implement standards in the field. For example, maintaining the length of straight ductwork required for an airflow sensor is usually difficult, requiring compromise.

Algorithm inputs can be assumed values (e.g., energy value of a unit volume of natural gas), one-time measurements (e.g., leakage area of a house), or time-series measurements (e.g., fuel consumption and outside and inside temperatures at the site). The algorithms may pertain to (1) utility level aggregates of buildings, (2) particular whole-building performance, or (3) performance of instrumented components.

Chapter 32 of the 2005 *ASHRAE Handbook—Fundamentals* contains a lengthy discussion on modeling procedures, and readers should consult this material for more information on modeling. In this chapter, the discussion is categorized differently, with a view toward procedures and issues related to field energy monitoring projects.

Table 6 provides a guide to selecting an analysis method. The error quotations are rough estimates for a single-building scenario.

Empirical Methods. Although empirical methods are the simplest, they can have large uncertainty and may generate little or no information for small sample sizes. The simplest empirical methods

are based on annual consumption values, tracking annual numbers and looking for degradation. Questions about building performance relative to other buildings are based on comparing certain performance indices between the building and an appropriate reference. The ENERGY STAR tools (www.energystar.gov) are probably the best-known performance comparison tools.

For commercial buildings, the most common simple index is the **energy use intensity (EUI)**, which is annual consumption, either by fuel type or summed over all fuel types, divided by the gross floor area [see MacDonald and Wasserman (1989) for a discussion of indices]. Comparison is often made only on the basis of general building type, which can ignore potentially large variations in how much floor area is heated or cooled, climate, number of workers in a building, number and type of computers in a building, and HVAC systems. Variations can be accommodated somewhat by stratifying the database from which the reference EUI is chosen. Computer simulations are often used to set reasonable comparison values.

The Commercial Buildings Energy Consumption Survey (CBECS) database [summarized in EIA (1998) and in Chapter 35] has been used to develop ENERGY STAR energy use benchmarking methods for several building types in the United States. Many of the building tools have been updated to 1999 data, and some are expected to be updated to data from the 2003 CBECS survey by 2007. Building types covered as of November 2004 include the following:

- Offices (general offices, financial centers, bank branches, and courthouses)
- K to 12 schools
- Supermarkets/grocery stores
- Hospitals (acute care and children's)
- Hotels/motels
- Residence halls/dormitories
- Warehouses (refrigerated and nonrefrigerated)
- Medical offices

For some of these building types, some secondary spaces are allowed:

- Computer data centers
- Garages and parking lots
- Swimming pools

Initial work in this area covered only electricity use for office buildings (Sharp 1996), but the methods have been extended to cover all fuels for the listed building types. Results show that electricity use of office buildings is most significantly explained by the number of workers in the building, number of computers, whether the building is owner-occupied, and number of operating hours each week. Only a subset of these parameters might be used to determine a benchmark within a specific census division. ENERGY STAR documentation on current tools and the performance normalization factors can be found at www.energystar.gov.

Table 6 Whole-Building Analysis Guidelines

| | Class of Method | | |
Project Goal	Empirical (Billing Data)*	Time-Integrated Model*	Dynamic Model
Building evaluation	Yes, but expect fluctuations in 20 to 30% range.	Yes, extra care needed beyond 15% uncertainty.	Yes, extra care needed beyond 10% uncertainty.
Building retrofit evaluation	Not generally applicable using monthly data, unless large samples are used. Requires daily data and various normalization techniques for reasonable accuracy.	Yes, but difficult beyond 15% uncertainty. Method cannot distinguish multiple retrofit effects.	Yes, can resolve 5% change with short-term tests. Can estimate multiple retrofit effects.
Component evaluation	Not applicable.	Not applicable unless submetering is done to supplement.	Yes, about 5% accuracy, but best with submetering.

Note: Error figures are approximate for total energy use in a single building. All methods improve with selection of more buildings.

*Accuracy can be improved by decreasing time step to weekly or daily. These methods are of little use when outdoor temperature approaches balance temperature.

Simple empirical methods applied to retrofit applications should include at least some periods of data on daily energy use and average daily temperature (recorded locally) to account for variations in occupancy and building schedules. Monthly EUI or billing data provide more information for empirical analysis and can be used for extended analysis of energy impacts of retrofit applications, for example, in **conditional demand analysis** (Hirst and Reed 1991). Monthly data can also be used to detect billing errors, improper equipment operation during unoccupied hours, and seasonal space condition problems (Haberl and Komor 1990a, 1990b). Daily data are often used in these analyses, and raw hourly total building consumption data, when available, provide more detailed information on occupied versus unoccupied performance. Hourly, daily, monthly, and annual EUI across buildings can be directly compared when reduced to average power per unit area (power density). To avoid false correlations, the method of analysis should have statistical significance that can be traced to realistic parameters (Haberl et al. 1996).

Model-Based Methods. These techniques allow a wide range of additional data normalization to potentially improve the accuracy of comparisons and provide estimates of cause-and-effect relations. The analyst must carefully define the system and postulate a useful form of the governing energy balance/system performance equation or system of equations. Explicit terms are retained for equipment or processes of particular interest. As part of the data analysis, whole-building data (driving forces and thermal or energy response) are used to determine the model's significant parameters. The parameters themselves can provide insight, although parameter interpretation can be difficult, particularly with time-integrated billing data methods. The model can then be used for normalization processes as well as future diagnostic and control applications. Two general classes of models are used in analysis methods: time-integrated methods and dynamic techniques (Balcomb et al. 1993). Simulation modeling results used for design of new buildings typically do not cover all energy used in a building and thus are usually difficult to compare with empirical data.

Time-integrated methods. Based on algebraic calculation of the building energy balance, time-integrated methods are often used before data comparison to correct annual consumption for variations in outside temperature, internal gains, and internal temperature (Busch et al. 1984; Claridge et al. 1991; Fels 1986; Haberl and Claridge 1987). This type of correction is essential for most retrofit applications.

Time-integrated methods can be used with whole-building energy consumption data (billing data) or with submetered end-use data. For example, standard time-integrated methods are often used to separately integrate end-use consumption data on heating, cooling (Ternes and Wilkes 1993), domestic water heating, and others for comparison and analysis. Time-integrated methods are generally reliable, as long as the following three conditions are accounted for:

- *Appropriate time step.* Generally, the time step should be as long as or longer than the response time of the building or building system for which energy use is being integrated. For example, the response of daylighting controls to natural illumination levels can be rapid, allowing short time steps for data integration. In contrast, the response of cooling system energy use to changes in cooling load can be comparatively slow. In this instance, either a time step long enough to average over these slow variations or a dynamic model should be used. In general, an appropriate time step should account for the physical behavior of the energy system(s) and the expression of this behavior in model parameters.

- *Linearity of model results.* Generally, time-integrated models should not be applied to data used to estimate nonlinear effects. Air infiltration, for example, is nonlinear when estimated using wind speed and inside/outside temperature difference data in

certain models. Estimation errors result if these parameters are independently time-integrated and then used to calculate air infiltration. These nonlinear effects should be modeled at each time step (each hour, for example).

- *End-use uniformity within data set.* End-use data sets should be **uniform** (i.e., should not inadvertently contain observations with measurements of end uses other than those intended). During mild weather, for example, HVAC systems may provide both heating and cooling over the course of a day, creating data observations of both heating and cooling measurements. In a time-integrated model of heating energy use, these cooling energy observations lead to error. These observations should be identified or otherwise flagged by their true end use.

For whole-building energy consumption data (billing data), reasonable results can be expected from heating analysis models when the building is dominantly responsive to inside/outside temperature differences. Billing data analysis yields little of interest when internal gains are large compared to skin loads, as in large commercial buildings and industrial applications. Daily, weekly, and monthly whole-building heating season consumption integration steps have been used (Claridge et al. 1991; Fels 1986; Sharp and MacDonald 1990; Ternes 1986). Cooling analysis results have been less reliable because cooling load is not strictly proportional to variable-base cooling degree-days (Fels 1986; Haberl et al. 1996; Kissock et al. 1992). Problems also arise when solar gains are dominant and vary by season.

Dynamic Techniques. Dynamic models, both **macrodynamic** (whole-building) or **microdynamic** (component-specific), offer great promise for reducing monitoring duration and increasing conclusion accuracy. Furthermore, individual effects from multiple measures and system interactions can be examined explicitly. Dynamic whole-building analysis is generally accompanied by detailed instrumentation of specific technologies.

Dynamic techniques create a dynamic physical model for the building, adjusting model parameters to fit experimental data (Duffy et al. 1988; Subbarao 1988). In residential applications, computer-controlled electric heaters can be used to maintain a steady interior temperature overnight, extracting from these data an experimental value for the building steady-state load coefficient. A cooldown period can also be used to extract information on internal building mass thermal storage. Daytime data can be used to renormalize the building response (computed from a microdynamic model) to solar radiation, which is particularly appropriate for buildings with glazing areas over 10% of the building floor area (Subbarao et al. 1986). Once the data with electric heaters have been taken, the building can be used as a dynamic calorimeter to assess the performance of auxiliary heating and cooling systems.

Similar techniques have been applied to commercial buildings (Burch et al. 1990; Norford et al. 1985). In these cases, delivered energy from the HVAC system must be monitored directly in lieu of using electric heaters. Because ventilation is a major variable in the building energy balance, outside airflow rate should also be monitored directly. Simultaneous heating and cooling, common in large buildings, requires a multizone treatment, which has not been adequately tested in any of the dynamic techniques.

Equipment-specific monitoring guidelines using dynamic modeling have been successfully tested in a variety of applications. For fans and pumps, relatively simple regression techniques from short-term monitoring provided accurate estimates of annual energy consumption when combined with an annual equipment load profile. For chillers, a thermodynamic model used with short-term monitoring captured the most important operating parameters for estimating installed annual energy performance. In all cases, the key to accurate model results was capturing a wide enough range of the independent load variable in monitored data to reflect annual operating characteristics (Phelan et al. 1997a, 1997b).

Part Six: Specify Field Data Monitoring Points

Careful specification of field monitoring points is critical to identifying variables that need to be monitored or measured in the field to produce required data.

The analysis method determines the data to be measured in the field. The simplest methods require no onsite instrumentation. As methods become more complex, data channels increase. For engineering field tests conducted with dynamic techniques, up to 100 data channels may be required.

Because metering projects are often conducted in buildings with changing conditions, special consideration must be given to identifying and monitoring significant changes in climate, systems, and operation during the monitoring period. Additional monitoring points may be required to measure variables that are assumed to be constant, insignificant, or related to other measured variables to draw sound conclusions from the measurements. Because the necessary data may be obtained in several ways, data analysts, equipment installers, and data acquisition system engineers should work together to develop tactics that best suit the project requirements. It is important to anticipate the need for supplemental measurements in response to project needs that may not become apparent until actual equipment installation occurs.

The cost of data collection is a nonlinear function of the number, accuracy, and duration of measurements that must be considered while planning within budget constraints. Costs per data point typically decrease as the number of points increases, but increase as accuracy requirements increase. Duration of monitoring can have many different effects. If the extent of data applications is unknown, such as in research projects, consideration should be given to the value of other concurrent measurements because the incremental cost of alternative analyses may be small.

For any project involving large amounts of data, data quality verification (see Part Eight) should be automated (Lopez and Haberl 1992). Although this may require adding monitoring points to facilitate energy balances or redundancy checks, the added costs are likely to be offset by savings in data verification for large projects.

If multiple sites are to be monitored, common protocols for selecting and describing all field monitoring points should be established so data can be more readily verified, normalized, compared, and averaged. Protocols also add consistency in selecting monitoring points. Pilot installations should be conducted to provide data for a test of the system and to ensure that the necessary data points have been properly specified and described.

Monitoring Equipment. General considerations in selecting monitoring equipment include the following:

- Evaluate equipment thoroughly under actual test conditions before committing to large-scale procurement. Particular attention should be paid to any sensitivity to power outages and to protection against power surges and lightning.
- Consider local setup and testing of complex data acquisition systems that are to be installed in the field.
- Avoid unproven data acquisition equipment (Sparks et al. 1992). Untested equipment, even if donated, may not be a good value.
- Consider costs and benefits of remote data interrogation and programming.
- Evaluate quality and reliability of data loggers and instrumentation; these issues may be more important than cost, particularly when data acquisition sites are distant.
- Verify vendor claims by calling references or obtaining performance guarantees.
- Consider portable battery-powered data loggers in lieu of hardwired loggers if the monitoring budget is limited and the length of the monitoring period is less than a few months.
- Ensure that monitoring equipment and installation methods are consistent with prevailing laws, building codes, and standards of good practice.

Using a building energy management system or direct digital control systems for data acquisition may decrease costs. This should be considered only when the sensors and their accuracy and limitations (scan rate, etc.) are thoroughly understood. When merging data from two data acquisition systems, problems may arise such as differing reliability and low data resolution (e.g., 1 kW resolution of a circuit that draws 10 kW fully loaded). These problems can often be avoided, however, by adding appropriate sensors and setting up custom logging or calculations with point, memory, and programming capacity.

Once the required field data monitoring points are specified, these requirements should be clearly communicated to all members of the project team to ensure that the actual monitoring points are accurately described. This can be accomplished by publishing handbooks for measurement plan development and equipment installation and by outlining procedures for diagnostic tests and technology assessments.

Because hardware needs vary considerably by project, specific selection guidelines are not provided here. However, general characteristics of data acquisition hardware components are shown in Table 7. Some typical concerns for selecting data acquisition

Table 7   General Characteristics of Data Acquisition System (DAS)

Types of DAS	Typical Use	Typical Data Retrieval	Comments
Manual readings	Total energy use	Monthly or daily written logs	Human factors may affect accuracy and reading period. Data must be manually entered for computer analysis.
Pulse counter, solid state (1, 4, or 8 channels)	Total energy use (some end use)	Polled by telephone to mainframe or minicomputer	Computer hardware and software is needed for transfer and conversion of pulse data. Can be expensive. Can handle large numbers of sites. User-friendly.
Stick-on battery powered logger (1 to 8 channels)	Diagnostics, technology assessment, end use	Monthly manual download to PC	Very useful for remote sites. Can record pulse counts, temperature, etc., up to thousands of records.
Plug-in A/D boards for PCs	Diagnostics, technology assessment, control	On-site real-time collection and storage	Usually small-quantity, unique applications. PC programming capability needed to set up data software and configure boards.
Simple field DAS (usually 16 to 32 channels)	Technology assessment, residential end use (some diagnostics)	Phone retrieval to host computer for primary storage (usually daily to weekly)	Can use PCs as hosts for data retrieval. Good A/D conversion available. Low cost per channel. Requires programming skills to set up field unit and configure communications for data transfer.
Advanced field DAS (usually >40 channels/ units)	Diagnostics, energy control systems, commercial end use	On-site real-time collection and data storage, or phone retrieval	Usually designed for single buildings. Can be PC-based or stand-alone unit. Can run applications/diagnostic programs. User-friendly.
Direct digital control or building automation system	On-site diagnostics, energy measurement and verification	Proprietary data collection procedures, manual or automated export to spreadsheet.	Requires significant coordination with building operation personnel. Sensor accuracy, calibration, and installation require confirmation. Good for projects with limited instrumentation budget.

hardware are outlined in Table 8. In general, data logger and instrumentation hardware should be standardized, with replacements available in the event of failure. Also consider redundant measurements for critical data components that are likely to fail, such as modems, flowmeters, shunt resistors on current transformers, and devices with moving parts (O'Neal et al. 1993). Some measurements that are more difficult to obtain accurately because of instrumentation limitations are summarized in Table 9.

Safety must be considered in equipment selection and installation. Installation teams of two or more individuals reduce risks. When contemplating thermal metering, the presence of asbestos insulation on water piping should be determined. Properly licensed trades personnel, such as an electrician or welder, should be a fundamental part of any team installing electrical monitoring equipment.

Table 8 Practical Concerns for Selecting and Using Data Acquisition Hardware

Components	Field Application Concerns
Data logger unit and peripherals	• Select equipment for field application. Flexible or adaptable input capabilities desirable. • Equipment should store data electronically for easy transfer to a computer. • Remote programming capability should be available to minimize on-site software modifications. • Avoid equipment with cooling fans. • Use high-quality, reliable communication devices or methods. • Make sure logger/computer and communication reset after power outage.
Cabling and interconnection hardware	• Use only signal-grade cable: shielded, twisted-pair with drain wire for analog signals. • Mitigate sources of common mode and normal mode signal noise.
Sensors	• Use rugged, reliable sensors rated for field application. • Use a signal splitter if sharing existing sensors or signals with other recorders or energy management control system (EMCS). • Select ranges so sensors operate at 50 to 75% of full scale. • Choose sensors that do not require special signal conditioning or power supply if possible. • Precalibrate sensors and recalibrate periodically. • When possible, use redundant channels to cross-check critical channels that can drift.

Table 9 Instrumentation Accuracy and Reliability

Instrument	Problems
Hygrometers	Drift, saturation and accuracy over time, need for calibration to remove temperature dependence; aspirated systems need to be cleaned periodically. Chilled mirror systems require frequent maintenance.
Flowmeters	Need for calibration, reliability. Moving parts prone to failure. Pipe size must be verified before calibration or installation.
Btu meters	60 Hz noise from surroundings, calibration.
Single-ended voltage	Grounding problems, spurious line voltages, 60 Hz noise.
Outdoor air temperature sensor	Must be properly shielded from solar radiation. Aspiration may reduce solar radiation effects but decrease long-term reliability.
RTD sensors	Signal wire length affects readings.
Power meters	Polarity of current transformers (CTs) often marked incorrectly, problems with shunt resistors and CT output. Devices should be checked before installation.

To prevent inadvertent tampering, occupants and maintenance personnel should be carefully briefed on what is being done and the purpose of sensors and equipment. Data loggers should have a dedicated (non-occupant-switchable) hard-wired power supply to prevent accidental power loss.

Sensors. Sensors should be selected to obtain each measurement on the field data list. Next, conversion and proportion constants should be specified for each sensor type, and the accuracy, resolution, and repeatability of each sensor should be noted. Sensors should be calibrated before they are installed in the field, preferably with a NIST-traceable calibration procedure. They should be checked periodically for drift, recalibrated, and then postcalibrated at the conclusion of the experiment (Haberl et al. 1996). Instrument calibration is particularly important for flow and power measurement.

Particular attention must be paid to sensor location. For example, if the method requires an average inside temperature, examine the potential for internal temperature variation; data from several temperature sensors must often be averaged. Alternatively, temperature sensors adjacent to HVAC thermostats detect the temperature to which the HVAC equipment reacts.

Scanning and Recording Intervals. Measurement frequency and data storage can affect the accuracy of results. Scanning differs from storage in that data channels may be read (scanned) many times per second, for example, whereas average data may be recorded and stored every 15 min. Most data loggers maintain temporary storage registers, accumulating an integrated average of channel readings from each scan. The average is then recorded at the specified interval.

After the channel list is compiled and sensor accuracy requirements established, scan rates should be assigned. Some sensors, such as inside and outside temperature sensors, may require low scan rates (once every 5 min). Others, such as total electric sensors, may contain high-frequency transients that require rapid sampling (many times per second). The scan rate must be fast enough to ensure that all significant effects are monitored.

The maximum sampling rate is usually programmed into the logger, and averages are stored at a specified time step (hourly). Some loggers can scan different channels at different rates. The logger's interrupt capability can also be used for rapid, infrequent transients. Interrupt channels signal the data logger to start monitoring an event only once it begins. In some cases, online computation of derived quantities must be considered. For example, if heat flow in an air duct is required, it can be computed from a differential temperature measurement multiplied by an air mass flow rate determined from a one-time measurement. However, it should be computed and totaled only when the fan is operating.

Part Seven: Resolve Data Product Accuracies

Data collected by monitoring equipment are usually used for the following purposes:

• Direct reporting of primary measurement data
• Reporting of secondary or deduced quantities (e.g., thermal energy consumed by a building, found by multiplying mass flow rate and temperature difference
• Subsequent interpretation and analyses (e.g., to develop a statistical model of energy used by a building versus outside dry-bulb temperature)

In all three cases, the value of the measurements is dramatically increased if the associated uncertainty can be quantified.

Basic Concepts. Uncertainty can be better understood in terms of confidence limits, which define the range of values that can be expected to include the true value with a stated probability (ASHRAE *Guideline* 2). Thus, a statement that the 95% confidence limits are 5.1 to 8.2 implies that the true value is between 5.1 and 8.2 in 19 out of 20 predictions or, more loosely, that we are 95% confident

that the true value lies between 5.1 and 8.2. For a given set of n observations with normal (Gaussian) error distribution, the total variance about the mean predicted value $\overline{X}'$ provides a direct indication of the confidence limits. Thus the "true" mean value X' of the random variable is bounded as follows:

$$\overline{X}' \pm (t_{\alpha/2,n-1}\sqrt{\sigma^2/n}) \tag{1}$$

where

α = level of significance
$\overline{X}'$ = mean predicted value of random variable X
$t_{\alpha/2,n-1}$ = t-statistic with probability of $1 - \alpha/2$ and $n - 1$ degrees of freedom (tabulated in most statistical textbooks)
n = number of observations, with Gaussian error distribution
σ^2 = estimated measurement variance

The terms **accuracy** and **precision** are often used to distinguish between bias errors and random errors. A set of measurements with small bias errors is said to have high accuracy, and a set of measurements with small random errors is said to have high precision. In repeated measurements of a given sample by the same technique (single-sample data), each measurement has the same bias. Bias errors include those that are (1) known and can be calibrated out, (2) negligible and are ignored, and (3) estimated and are included in the uncertainty analysis. It is usually difficult to estimate bias limits, and this effect is often overlooked. However, a proper error analysis should include bias error, which is usually written as a plus-minus error. ASME *Standard* PTC 19.1 has a more complete discussion.

Because bias errors b_m and random errors ε_m are usually uncorrelated, measurement variance σ^2 can be expressed as

$$\sigma^2_{meas}(b_m,\varepsilon_m) = \sigma^2(b_m) + \sigma^2(\varepsilon_m) \tag{2}$$

For further information on uncertainty, see Chapter 14 of the 2005 *ASHRAE Handbook—Fundamentals*. For more information on uncertainty calculation methods related specifically to building energy savings monitoring, see ASHRAE *Guideline* 14, Annex B.

Primary Measurement Uncertainty. Sensor and measuring equipment manufacturers usually specify measurement variances; frequent recalibration minimizes bias errors. As indicated by Equation (1), increasing the number of measurements n reduces the uncertainty bounds.

Uncertainty in Derived Quantities. Once a specific algorithm or equation for obtaining final data from physical measurements has been established, standard techniques can be used to incorporate primary measurement uncertainties into the final data product. For random errors, the Kline and McClintock (1953) error propagation method, based on a first-order Taylor series expansion, is widely used to determine measurement uncertainties in derived variables in single-sample experiments. Bias errors are difficult to account for; the usual practice is to calibrate them out and exclude them from the uncertainty analysis.

Uncertainty in Statistical Regression Models. Statistical regression models developed from measured data are usually used for predictive purposes. Measurement errors are much smaller than model errors, which arise because the regression model is imperfect; that is, it is unable to explain the entire variation in the regressor variable (Box 1978). Measurement error is inherently contained in the identified model, so total prediction variance is simply given by the model prediction uncertainty.

Determining prediction errors from regression models is subject to different types of problems. The various sources of error can be classified into three categories (Reddy et al. 1998):

• Model *misspecification* errors occur because the functional form of the regression model is usually an approximation of the true driving function of the response variable.

• Model *prediction* errors occur because a model is never perfect.
• Model *extrapolation* errors occur when a model is used for prediction outside the region covered by the data from which the model was developed. Models developed from short data sets, which do not satisfactorily represent the annual behavior of the system, are subject to this error. This error cannot be quantified in statistical terms alone, but certain experimental conditions are likely to lead to accurate predictive models. This falls under the purview of experimental design (Box 1978).

Misspecification and extrapolation errors are likely to introduce bias and random error. If ordinary least-squares regression is used for parameter estimation, and if the model is subsequently used for prediction, model prediction will be purely random. Thus, models identified from short data sets and used to predict seasonal or annual energy use are affected by misspecification and extrapolation errors.

The least-squares method of calculating linear regression coefficients cannot produce unbiased estimators of slope and intercept if there are errors associated with measuring the predictor variable. The uncertainty analysis methodology developed for in situ equipment testing uses standard linear regression practices to find the functional relationship and then estimates the increased uncertainty in the regression prediction because of random and bias errors in both variable measurements (Phelan et al. 1996).

Experimental Design. Errors can also be estimated based on historical experience (e.g., using results from previous similar projects). Alternatively, a pilot study can obtain an estimate of potential errors in a proposed analysis. Some estimate of potential error must be available to determine whether project goals and objectives are reasonable.

Estimating data uncertainty is one part of the iterative procedure associated with proper experimental design. If the final data product uncertainty determined using the given evaluation procedure is unacceptable, uncertainty can be reduced in one or more of the following ways:

• Reducing overall measurement uncertainty (improving sensor precision)
• Increasing the duration of monitoring to average out stochastic variations
• Increasing the number of buildings tested (sample size)

On the other hand, if simulations or estimates indicate that the expected bias in the final data products is unacceptable, the bias may be reduced by one or more of the following steps:

• Adding sensors to get an unbiased measurement of the quantity
• Using more detailed models and analysis procedures
• Increasing data acquisition frequency, combined with a more detailed model, to address biases from sensor or system nonlinearities.

Accuracy Versus Cost. The need for accuracy must be carefully balanced against measurement and analysis costs. Accuracy loss can stem from instrumentation or measurement error, normalization or model error, sampling or statistical error, and errors of assumptions. Each of these sources can be controlled to varying degrees. However, in general, more accurate methods follow the law of diminishing returns, in which further reductions in error come at progressively greater expense.

Because of this tradeoff, the optimal measurement solution is usually found by an iterative approach, where incremental improvements in accuracy are assessed relative to the increase in measurement cost. Such optimization requires that a value be placed on increasing levels of accuracy. One method of evaluating the uncertainty of a proposed method is to calculate results using the highest and lowest values in the confidence interval. The difference between these values can be translated into a monetary amount that is at risk. The question that must be answered is whether further measurement investment is warranted to reduce this risk.

Table 10   Quality Assurance Elements

Time Frame	Hardware	Engineering Data	Characteristics Data
Initial start-up	Bench calibration (1)	Installation verification (1)	Field verification (1)
	Field calibration (1)	Collection verification (1,2)	Completeness check (1)
	Installation verification (1)	Processing verification (1,2)	Reasonableness check (1,2)
		Result production (1,2)	Result production (1,2)
Ongoing	Functional testing (1)	Quality checking (2)	Problem diagnosis (3)
	Failure mode diagnosis (3)	Reasonableness checking (2)	Data reconstruction (4)
	Repair/maintenance (4)	Failure mode diagnosis (3)	Change control (1)
	Change control (1)	Data reconstruction (4)	
		Change control (1)	
Periodic	Preventive maintenance (1)	Summary report preparation and review (2)	Scheduled updates/resurveys (1)
	Calibration (1)		Summary report preparation and review (2)

(1) Actions to ensure good data.   (2) Actions to check data quality.   (3) Actions to diagnose problems.   (4) Actions to repair problems.

Part Eight: Specify Verification and Quality Assurance Procedures

Establishing and using data quality assurance (QA) procedures can be very important to the success of a field monitoring project. The amount and importance of the data to be collected help determine the extent and formality of QA procedures. For most projects, the entire data path, from sensor installation to procedures that generate results for the final report, should be considered for verification tests. In addition, the data flow path should be checked routinely for failure of sensors or test equipment, as well as unexpected or unauthorized modifications to equipment.

QA often requires complex data handling. Building energy monitoring projects collect data from sensors and manipulate those data into results. Data handling in a project with only a few sensors and required readings can consist of a relatively simple data flow on paper. Computers, which are generally used in one or more stages of the process, require a different level of process documentation because much of what occurs has no direct paper trail.

Computers facilitate collection of large data sets and increase project complexity. To maximize automation, computers require development of specific software. Often, separate computers are involved in each step, so passing information from one computer to another must be automated in large projects. To move data as smoothly as possible, an automated **data pipeline** should be developed; this minimizes the delay from data collection to results production and maximizes the cost-effectiveness of the entire project.

Because collected data are valuable, data back-up procedures must also be part of QA. At a minimum, the basic data, either raw or first-level processed, should be stored in at least one and preferably two different back-up locations, apart from the main data storage location, to allow data recovery in case of hardware failure, fire, vandalism, etc. Back-ups should occur at regular intervals, probably not less than weekly for larger projects.

Automated data verification should be used when possible. Frequent data acquisition (preferably automated) with a quality control review of summarized and plotted data is essential to ensure that reliable data are collected. Verification procedures should be performed at frequent intervals (daily or weekly), depending on the importance of missing data. This minimizes data loss because of equipment failure and/or changes at a building site. It also allows processed information to be applied quickly.

The following QA actions should take place:

- Calibrate hardware and establish a good control procedure for collection of data. Use NIST-traceable calibration methods.
- Verify data, check for reasonableness, and prepare a summary report to ensure data quality after collection.
- Perform initial analysis of data. Significant findings may lead to changes in procedures for checking data quality.

- Thoroughly document and control procedures applied to remedy problems. These procedures may entail changes in hardware or collected data (such as data reconstruction), which can have a fundamental effect on the results reported.
- Archive raw data obtained from the site to ensure project integrity.

Three aspects of a monitoring project that require QA are shown in Table 10: hardware, engineering data, and characteristics data. Three QA reviews are necessary for each aspect: (1) initial QA confirms that the project starts correctly; (2) ongoing QA confirms that information collected by the project continues to satisfy quality requirements; and (3) periodic QA involves additional checks, established at the beginning of the project, to ensure continued performance at an acceptable quality level.

Information about data quality and the QA process should be readily available to data users. Otherwise, significant analytical resources may be expended to determine data quality, or the analyses may never be performed because of uncertainties.

Part Nine: Specify Recording and Data Exchange Formats

This step specifies the formats in which data will be supplied to the end user or other data analysts. Both raw and processed (adjusted for missing data or anomalous readings) data formats should be specified. In addition, if supplemental analyses are planned, the medium and format to be used (type of disk, possibly magnetic tape type, spreadsheet, character encoding standard) should be specified. These requirements can be determined by analyzing the software data format specifications. Common formats for raw data are comma- and blank-delimited American Standard Code for Information Exchange (ASCII), which do not require data conversion.

Data documentation is essential for all monitoring projects, especially when several organizations are involved. Data usability is improved by specifying and adhering to data recording and exchange formats. Most data transfer problems are related to inadequate documentation. Other problems include hardware or software incompatibility, errors in electronic storage media, errors or inconsistencies in the data, and transmittal of the wrong data set. The following precautions can prevent some of these problems:

- Provide documentation to accompany the data transfer (Table 11). Because these guidelines apply to general data, models, programs, and other types of information, items listed in Table 11 may not apply to every case.
- Provide documentation of transfer media, including the computer operating system, software used to create the files, media format (e.g., ASCII, application-specific), and media characteristics (note that many CD-ROM formats exist, some of which are proprietary and not widely used, so care should be taken to use commonly available methods).

Table 11 Documentation Included with Computer Data to be Transferred

1. Title and/or acronym
2. Contact person (name, address, phone number)
3. Description of file (number of records, geographic coverage, spatial resolution, time period covered, temporal resolution, sampling methods, uncertainty/reliability)
4. Definition of data values (variable names, units, codes, missing value representation, location, method of measurement, variable derivation)
5. Original uses of file
6. Size of file (number of records, bytes)
7. Original source (person, agency, citation)
8. Pertinent references (complete citation) on materials providing additional information
9. Appropriate reference citation for the file
10. Credit line (for use in acknowledgments)
11. Restrictions on use of data/program
12. Disclaimer, such as
    - Unverified data; use at your own risk.
    - Draft data; use with caution.
    - Clean data to the best of our knowledge. Please let us know of any possible errors or questionable values.
    - Program under development.
    - Program tested under the following conditions (conditions specified by author).

- Provide procedures to check the accuracy and completeness of data transfer, including statistics or frequency counts for variables and hard-copy versions of the file. Test input data and corresponding output results for models on other programs.
- Keep all raw data, including erroneous records.
- Convert and correct data; save routines for later use.
- Limit equipment access to authorized individuals.
- Check incoming data soon after they are collected, using simple time-series and *x-y* inspection plots.
- Automate as many routines as possible to avoid operator error.

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CHAPTER 41

SUPERVISORY CONTROL STRATEGIES AND OPTIMIZATION

COMPUTERIZED energy management and control systems provide an excellent means of reducing utility costs associated with maintaining environmental conditions in commercial buildings. These systems can incorporate advanced control strategies that respond to changing weather and building conditions and minimize operating costs.This chapter focuses on the opportunities and control strategies associated with using computerized control for centralized cooling and heating systems.

HVAC systems are typically controlled using a two-level control structure. Lower-level **local-loop control** of a single set point is provided by an actuator. For example, the supply air temperature from a cooling coil is controlled by adjusting the opening of a valve that provides chilled water to the coil. The upper control level, **supervisory control**, specifies set points and other time-dependent modes of operation.

The performance of large, commercial HVAC systems can be improved through better local-loop and supervisory control. Proper tuning of local-loop controllers can enhance comfort, reduce energy use, and increase component life. Set points and operating modes for cooling plant equipment can be adjusted by the supervisor to maximize overall operating efficiency. Dynamic control strategies for ice or chilled-water storage systems can significantly reduce on-peak electrical energy and demand costs to minimize total utility costs. Similarly, thermal storage inherent in a building's structure can be dynamically controlled to minimize utility costs. In general, strategies that take advantage of thermal storage work best when forecasts of future energy requirements are available.

The chapter is divided into three major sections. The first section defines the systems and control variables considered and presents background on the effects and opportunities associated with adjusting control variables. The second section, intended for practitioners, presents a number of supervisory control strategies that can be implemented in computerized control systems. Finally, the third section presents basic methods for optimization of systems both with and without significant thermal energy storage and is intended for researchers and developers of advanced control strategies.

BACKGROUND

SYSTEMS, DEFINITIONS, AND CONTROL VARIABLES

Figures 1 and 2 show schematics of typical centralized cooling and heating systems for which control strategies are presented in

this chapter. For cooling systems, the strategies generally assume that the equipment is electrically driven and that heat is rejected to the environment by cooling towers. For heating systems, boilers may be fired by a variety of fuels or powered by electricity, but are typically fired from either natural gas or #2 or #6 fuel oil. However, some strategies apply to any type of system (e.g., return from night setup or setback). For describing different systems and controls, it is useful to divide the system into the subsystems depicted in Figures 1 and 2: air distribution system, chilled-/hot-water loop, chiller/boiler plant, condenser water loop.
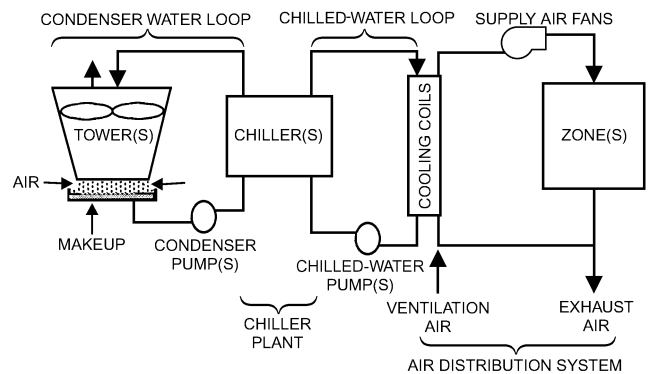
Fig. 1   Schematic of Chilled-Water Cooling System
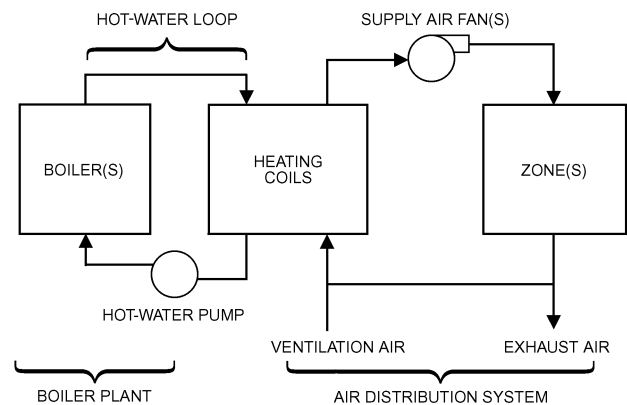
Fig. 2   Schematic of Hot-Water Heating System

The preparation of this chapter is assigned to TC 7.4, Building Operation Dynamics.

Subsystems

Air Distribution Systems. An air distribution system includes terminal units (VAV boxes, etc.), air-handling units (AHUs), ducts, and controls. In each AHU, ventilation air is mixed with return air from the zones and fed to the cooling/heating coil. Typically, an **economizer control** selects between minimum and maximum ventilation air, depending on the condition of the outside air relative to the conditions of the return air. Under certain outside air conditions, the AHU dampers may be modulated to provide a mixed-air condition that can satisfy the cooling load without the need for mechanical cooling.

A local-loop controller adjusts the flow of water through the air handler cooling/heating coil using a two- or three-way valve to maintain a specified set-point temperature for air downstream of the cooling/heating coil. This control variable is called the **supply air temperature** (the air temperature supplied to the zones may differ from the supply air temperature because of heat transfer in the ductwork and local reheat). The value of the supply air temperature set point affects energy consumption, and can be adjusted by the supervisory control system.

Two different types of zone controls are described in this chapter: constant air volume (CAV) and variable air volume (VAV). **CAV systems** have fixed-speed fans and provide no feedback control of airflow to the zones. For this system, zone temperature is controlled to a set point using a feedback controller that regulates the amount of local **reheat** applied to the air entering each zone. With a **VAV system**, a feedback controller regulates airflow to each zone to maintain zone temperature set points. Zone airflows are regulated using dampers located in VAV boxes in each zone. VAV systems also incorporate feedback control of the primary airflow through various means of fan capacity control. Typically, inputs to a fan outlet damper, inlet vanes, blade pitch, or variable-speed motor are adjusted to maintain a **duct static pressure** set point in the supply duct, as described in Chapter 46.

Zone temperature set points are typically fixed values within the comfort zone during the occupied time, and zone humidity is allowed to "float" within a range dictated by the system design and choice of the supply air set-point temperature. **Night setup** is often used in summer to raise the zone temperature set points during unoccupied times and reduce cooling requirements. Similarly, **night setback** is often used in winter to lower the zone temperature set points during unoccupied times and reduce heating requirements. Setup and setback can also be used during occupied periods to temporarily curtail energy consumption.

Chilled-/Hot-Water/Steam Loop. The chilled-/hot-water or steam loop consists of pumps, pipes, valves, and controls. Two different types of pumping systems are considered in this chapter: primary and primary/secondary. With a **primary pumping** system, a single piping loop is used and water that flows through the chiller or boiler also flows through the cooling or heating coils. When steam is used, a steam-piping loop sends steam to a hot-water converter, returning hot condensate back to the boiler. Another piping loop then carries hot water through the heating coils. Often, fixed-speed pumps are used with their control dedicated to chiller or boiler control. **Dedicated control** means that each pump is cycled on and off with the chiller or boiler that it serves. Systems with fixed-speed pumps and two-way cooling or heating coil valves often incorporate a **water bypass valve** to maintain relatively constant flow rates and reduce system pressure drop and pumping costs at low loads. The valve is typically controlled to maintain a fixed pressure difference between the main supply and return lines. This set point is called the **chilled-** or **hot-water loop differential pressure**. Sometimes, primary systems use one or more variable-speed pumps to further reduce pumping costs at low loads. In this case, water bypass is not used and pumps are controlled directly to maintain a water loop differential pressure set point.

Primary/secondary chilled- or hot-water systems are designed specifically for variable-speed pumping. In the primary loop, fixed-speed pumps provide a relatively constant flow of water to the chillers or boilers. This design ensures good chiller or boiler performance and, for chilled-water systems, reduces the risk of freezing on evaporator tubes. The secondary loop incorporates one or more variable-speed pumps that are controlled to maintain a water loop differential pressure set point. The primary and secondary loops may be separated by a heat exchanger, but it is more common to use direct coupling with a common pipe.

Chiller or Boiler Plant. One or more chillers or boilers, typically arranged in parallel with dedicated pumps, provide the primary source of cooling or heating for the system. Individual feedback controllers adjust the capacity of each chiller or boiler to maintain a specified **supply water temperature** (or steam header pressure for steam boilers). Additional control variables include the number of chillers or boilers operating and the relative loading for each. For a given total cooling or heating requirement, individual chiller or boiler loads can be controlled by using different water supply set points for constant individual flow or by adjusting individual flows for identical set points.

Cool thermal storage can also be used in combination with chillers to provide cooling during occupied periods. During the night, when commercial buildings are unoccupied, the primary cooling equipment is used to cool the thermal storage medium for use the next day. During occupied times, the combination of the primary cooling system and storage must meet the building cooling requirements. The use of thermal storage can significantly reduce the costs of providing cooling in commercial buildings by reducing on-peak demand and energy costs. The term **charging** is often used to describe the cooling of storage, and **discharging** describes the use of storage to provide cooling. Control of thermal storage is defined by the manner in which the storage medium is charged and discharged over time. This control problem differs from control of other system variables in that operating costs depend on a time history of charging and discharging over several hours.

Condenser Water Loop. The condenser water loop consists of cooling towers, pumps, piping, and controls. Cooling towers reject heat to the environment through heat transfer and possibly evaporation (for wet towers) to the ambient air. Typically, large towers incorporate multiple cells sharing a common sump with individual fans having two or more speed settings. Often, a feedback controller adjusts tower fan speeds to maintain a temperature set point for water leaving the cooling tower, termed the **condenser water supply temperature**. Typically, condenser water pumps are dedicated to individual chillers (i.e., each pump is cycled on and off with the chiller it serves).

Control Variables

Control of a VAV cooling system (see Figure 1) responds to changes in building cooling requirements. As the cooling load increases, the zone temperature rises as energy gains to the zone air increase. The zone controller responds to higher temperatures by increasing local flow of cool air by opening a damper. This action reduces static pressure in the primary supply duct, which causes the fan controller to create additional airflow. With greater airflow, the supply air temperature of the cooling coils increases, which causes the air handler feedback controller to increase the water flow by opening the cooling coil valves. This increases the chilled-water flow and heat transfer to the chilled water (i.e., the cooling load).

Control of a hot-water heating system (Figure 2) is similar. As the heating load increases, the zone temperature falls as energy gains to the zone air decrease. The zone controller responds to lower temperatures by opening a control valve and increasing the flow of hot water through the local reheat coil. The supply airflow rate is usually maintained at its minimum value when a VAV system is in heating mode. Increasing water flow through the reheat coils

reduces the temperature of the water returned to the boiler. With lower return water temperature, the supply water temperature drops, which causes the feedback controller to increase the boiler firing rate to maintain the desired supply water temperature.

For both heating and cooling, an increase in the building load results in an increase in water flow rate, which is ultimately propagated through the central system. For fixed-speed chilled- or hot-water pumps, the differential pressure controller closes the chilled- or hot-water bypass valve and keeps the overall flow relatively constant. For variable-speed pumping, the differential pressure controller increases pump speed. In a chilled-water system, the return water temperature and/ or flow rate to the chillers increases, leading to an increase in the chilled-water supply temperature. The chiller controller responds by increasing the chiller cooling capacity to maintain the chilled-water supply set point (and match the cooling coil loads). The increased energy removed by the chiller increases the heat rejected to the condenser water loop, which increases the temperature of water leaving the condenser. The increased water temperature entering the cooling tower increases the water temperature leaving the tower. The tower controller responds to the higher condenser water supply temperature and increases the tower airflow. At some load, the current set of operating chillers is not sufficient to meet the load (i.e., maintain the chilled-water supply set points) and an additional chiller is brought online. For a hot-water system, the return water temperature and/or flow rate to the boilers decreases, leading to a decrease in the hot-water supply temperature. The boiler controller responds by increasing the boiler heating capacity to maintain the hot-water supply set point (and match the heating coil loads).

For all-electric cooling without thermal storage, minimizing power at each point in time is equivalent to minimizing energy costs. Therefore, supervisory control variables should be chosen to maximize the **coefficient of performance (COP)** of the system at all times while meeting the building load requirements. The COP is defined as the ratio of total system power consumption to total cooling load. In addition to the control variables, the COP depends primarily on the cooling load and the ambient wet- and dry-bulb temperatures. Often, the cooling load is expressed in a dimensionless form as a part-load ratio (PLR), which is the cooling load under a given condition divided by the design cooling capacity.

For cooling or heating systems with thermal storage, performance depends on the time history of charging and discharging. In this case, controls should minimize operating costs integrated over the billing period. In addition, safety features that minimize the risk of prematurely depleting storage capacity are important.

For any of these scenarios, several local-loop controllers respond to load change to maintain specified set points. A supervisory controller establishes modes of operation and chooses (or resets) values of set points. At any given time, cooling or heating needs can be met with various combinations of modes of operation and set points. This chapter discusses several methods for determining supervisory control variables that provide good overall performance.

Sampling Intervals for Reset Controls

Proper sampling intervals are required when resetting the set point for certain proportional-integral (PI) feedback control loops to prevent oscillation of the process variable in those loops. In general, the sampling time interval between reset commands should be greater than the settling time for the loop. For example, resetting both the chilled-water supply temperature set point and cooling coil discharge air temperature set point is necessary for optimal control. In this case, resetting the set points for chilled-water supply temperature and cooling coil discharge air temperature should not occur simultaneously, but at staggered intervals; the interval of reset for either loop should be greater than the settling time for the coil (the time for the discharge air temperature of the coil to reach a new steady-state temperature).

For cascaded loops, the sampling interval between reset commands should be greater than the settling time for the slower loop. An example of a cascaded loop is a VAV box controller with its flow set point determined from the space temperature of its associated zone, and the box damper controlled to maintain the flow set point. For example, in resetting static pressure set point on a variable-speed air handler fan based on VAV box damper position, the interval between resets should be greater than the settling time of the flow control loop in a pressure-independent VAV box. (Settling time in this example is the time for the flow rate to reach a new steady-state value.)

OPTIMIZING CONTROLS FOR BOILERS

Almost two-thirds of fossil fuel consumption in the United States involves use of a boiler, furnace, or other fired system (Parker et al. 1997). Unlike many electric-driven systems, boilers and fired systems are not inherently energy efficient because their source energy is produced from on-site combustion. Boiler systems in many heating applications can be operated automatically by energy management and control systems to reduce utility costs associated with maintaining proper environmental conditions. Boiler efficiency depends on many factors, such as combustion airflow rate, load factor, and water temperature in hot-water boilers (or pressure for steam boilers). Opportunities for energy and cost reduction in boiler plants include excess air control, sequencing and loading of multiple boilers, and resetting the hot-water supply temperature set point (for hot-water boilers) or the steam pressure set point (for steam boilers) (Dyer and Maples 1981).

Excess Air in the Combustion Process

Combustion would occur with greatest efficiency if air and fuel could be mixed in the exact proportions indicated in the chemical reaction equation. This is called **stoichiometric combustion**. The ratio of the volume of air needed to burn completely one unit volume of the fuel is known as the **stoichiometric air/fuel ratio**. The heat released when the fuel burns completely is known as the **heat of combustion**.

In practice, it is impossible to achieve stoichiometric combustion because burners cannot mix air and fuel perfectly. In combustion processes, **excess air** is generally defined as air introduced above the stoichiometric or theoretical amount required for complete combustion of the fuel. Only the minimum amount of excess air should be supplied to the burner to ensure complete combustion; more than this amount increases the heat rejected to the stack and reduces efficiency. Combustion efficiency depends on the amount of excess air (or O_2) in the flue gas, stack temperature rise above burner inlet air temperature, and amount of unburned hydrocarbons. As shown in Figure 3, combustion efficiency drops sharply when deficient air is supplied to the burner because the amount of unburned hydrocarbons rises sharply, thereby wasting fuel. Operating a boiler with high excess air also heats the air unnecessarily, resulting in lower combustion efficiency. Combustion efficiency is optimized when excess air is reduced to the minimum.

To determine the minimum excess air for a particular boiler, flue gas combustible content as a function of excess O_2 should be charted as shown in Figure 4. For a gas-fueled boiler, carbon monoxide should be monitored; for liquid or solid fuel, monitor the smoke spot number (SSN). Different firing rates should be considered because the excess air minimum varies with the firing rate (percent load). Figure 4 shows curves for high and low firing rates. As shown, low firing rates generally produce a more gradual curve; high-rate curves are steeper. For burners and firing rates with a steep combustible content curve, small changes in the amount of excess O_2 may cause unstable operation. The optimal control set point for excess air should generally be 0.5 to 1% above minimum, to allow for slight variations in fuel composition, intake air temperature and

**Fig. 3   Effect of Percent of Excess Air on
Combustion Efficiency**

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LIVE GRAPH
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**Fig. 4   Hypothetical CO-O$_2$ Characteristic Combustion
Curves for a Gas-Fired Industrial Boiler**

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Table 1   Typical Optimum Excess Air for Various Boiler Types

Fuel Type	Firing Method	Optimum Excess Air, %	Equivalent O$_2$ (by Volume)
Natural gas	Natural draft	20-30	4-5
	Forced draft	5-10	1-2
	Low excess air	0.4-2.0	0.1-0.5
Propane	—	5-10	1-2
Coke oven gas	—	5-10	1-2
No. 2 oil	Rotary cup	15-20	3-4
	Air-atomized	10-15	2-3
	Steam-atomized	10-15	2-3
No. 6 oil	Steam-atomized	10-15	2-3
Coal	Pulverized	15-20	3-3.5
	Stoker	20-30	3.5-5
	Cyclone	7-15	1.5-3

Source: Parker et al. (1997). Copyright 1997 by Fairmont Press, Inc., 700 Indian Trail,
  Lilburn, GA 30047, www.fairmontpress.com. Reprinted by permission from *Energy
  Management Handbook*.

typically 1; for No. 6 fuel oil, SSN = 4. However, for any fuel used,
local environmental regulations may require lower limits.

To maintain safe unit output conditions, excess air requirements
may be greater than the levels indicated in this table. This condition
may arise when operating loads are substantially less than the
design rating. Where possible, check the vendor's predicted perfor-
mance curves. If they are unavailable, excess air should be reduced
to minimum levels consistent with satisfactory output.

Oxygen Trim Control

An oxygen trim control system adjusts the airflow rate using an
electromechanical actuator mounted on the boiler's forced-draft fan
damper linkage, and measures excess oxygen using a zirconium
oxide mounted in the boiler stack. The oxygen sensor signal is com-
pared with a set point value obtained from the boiler's excess air set
point curve for the given firing rate. The oxygen trim controller
adjusts ("trims") the damper setting to regulate the oxygen level in
the boiler stack at this set point. In the event of an electronic failure,
the boiler defaults to the air setting determined by the mechanical
linkages.

Carbon Monoxide Trim Control

Carbon monoxide trim control systems are also used to control
excess air, and offer several advantages over oxygen trim systems.
In carbon monoxide trim systems, the amount of unburned fuel (in
the form of carbon monoxide) in the flue gas is measured directly by
a carbon monoxide sensor and the air/fuel ratio control is set to
actual combustion conditions rather than preset oxygen levels.
Thus, the system continuously controls for minimum excess air.
Carbon monoxide trim systems are also independent of fuel type
and are virtually unaffected by combustion air temperature, humid-
ity, and barometric pressure conditions. However, they cost more
than oxygen trim systems because of the expense of the carbon
monoxide sensor. Also, the carbon monoxide level in the boiler
stack is not always a measure of excess air. A dirty burner, poor
atomization, flame chilling, flame impingement on the boiler tubes,
or poor fuel mixing can also raise the carbon monoxide level in the
boiler stack (Taplin 1998).

Sequencing and Loading of Multiple Boilers

Generally, boilers operate most efficiently at a 65 to 85% full-load
rating. Boiler efficiencies fall off at higher and lower load points,
with the decrease most pronounced at low load conditions. Boiler
efficiency can be calculated by means of stack temperature and per-
cent O$_2$ (or, percent excess air) in the boiler stack for a given fuel
type. Part-load curves of boiler efficiency versus hot-water or steam

humidity, barometric pressure, and control system characteristics.
Table 1 lists typical, normally attainable optimum excess air levels,
classified by fuel type and firing method.

Carbon monoxide upper control limits vary with the boiler fuel
used. The CO limit for gas-fired boilers may be set typically at
400, 200, or 100 ppm. For No. 2 fuel oil, the maximum SSN is

load should be developed for each boiler. These curves should be dynamically updated at discrete load levels based on the hot-water or steam plant characteristics to allow the control strategy to continuously predict the input fuel requirement for any given heat load. When the hot-water temperature or steam pressure drops below set point for the predetermined time interval (e.g., 5 min), the most efficient combination of boilers must be selected and turned on to meet the load. The least efficient boiler should be shut down and banked in hot standby if its capacity drops below the spare capacity of the current number of boilers operating (or, for primary/secondary hot-water systems, if the flow rate of the associated primary hot-water pump is less than the difference between primary and secondary hot-water flow rates) for a predetermined time interval (e.g., 5 min). The spare capacity of the current online boilers is equal to their full-load capacity minus the current hot water load.

Resetting Supply Water Temperature and Pressure

Standby losses are reduced and overall efficiencies enhanced by operating hot-water boilers at the lowest acceptable temperature. Condensing boilers achieve significantly higher combustion efficiencies at water temperatures below the dew point when they are operating in condensing mode (see Chapter 27 in the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*). Hot-water boilers of this type are very efficient at part-load operation when a high water temperature is not required. Energy savings are therefore possible if the supply water temperature is maintained at the minimum level required to satisfy the largest heating load. However, to minimize condensation of flue gases and consequent boiler damage from acid, water temperature should not be reset below that recommended by the boiler manufacturer (typically 140°F).

Similarly, energy can be saved in steam heating systems by maintaining supply pressure at the minimum level required to satisfy the largest heating load.

In practice, reset control is only possible if boiler controls interface with the energy management and control system.

Operating Constraints

Note that there are practical limitations on the extent of automatic operation if damage to the boiler is to be prevented. Control strategies to reduce boiler energy consumption can also conflict with recommended boiler operating practice. For example, in addition to flue gas condensation concerns mentioned previously, rapid changes in boiler metal temperature (**thermal shock**) brought about by abrupt changes in boiler water temperature or flow, firing rate, or air temperature entering the boiler should be avoided. The repeated occurrence of these conditions weakens the metal and leads to cracking and/or loose tubes. It is therefore important to follow all of the recommendations of the American Boiler Manufacturers Association (ABMA 1998).

OPTIMIZING CONTROLS FOR COOLING WITHOUT STORAGE

Figure 5 depicts multiple chillers, cooling towers, and pumps providing chilled water to air-handling units to cool air that is supplied to building zones. At any given time, cooling needs may be met with different modes of operation and set points. However, one set of control set points and modes results in minimum power consumption. This optimal control point results from tradeoffs between the energy consumption of different components. For instance, increasing the number of cooling tower cells (or fan speeds) increases fan power but reduces chiller power because the temperature of the water supplied to the chiller's condenser is decreased. Similarly, increasing condenser water flow by adding pumps (or increasing pump speed) decreases chiller power but increases pump power.

Similar tradeoffs exist for the chilled-water loop variables of systems with variable-speed chilled-water pumps and air handler fans.
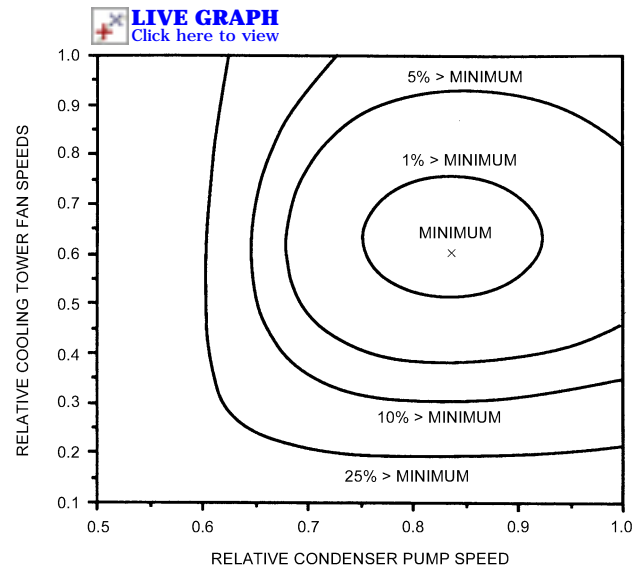
Fig. 5 Example Power Contours for Condenser-Loop Control Variables

For instance, increasing the chilled-water set point reduces chiller power but increases pump power because greater flow is needed to meet the load. Increasing the supply air set point increases fan power, but decreases pump power.

Figure 5 illustrates the sensitivity of the total power consumption to condenser water-loop controls (from Braun et al. 1989a) for a single chiller load, ambient wet-bulb temperature, and chilled-water supply temperature. Contours of constant power consumption are plotted versus cooling tower fan and condenser water pump speed for a system with variable-speed fans and pumps. Near the optimum, power consumption is not sensitive to either of these control variables, but increases significantly away from the optimum. The rate of increase in power consumption is particularly large at low condenser pump speeds. A minimum pump speed is necessary to overcome the static pressure associated with the height of water discharge in the cooling tower above the sump. As the pump speed approaches this value, condenser flow approaches zero and chiller power increases dramatically. A pump speed that is too high is generally better than one that is too low. The broad area near the optimum indicates that, for a given load, the optimal setting does not need to be accurately determined. However, optimal settings change significantly when there are widely varying chiller loads and ambient wet-bulb temperature.

Figure 6 illustrates the sensitivity of power consumption to chilled-water and supply air set-point temperatures for a system with variable-speed chilled-water pumps and air handler fans (from Braun et al. 1989a). Within about 3°F of the optimum values, power consumption is within 1% of the minimum. Outside this range, sensitivity to the set points increases significantly. The penalty associated with operation away from the optimum is greater in the direction of smaller differences between the supply air and chilled-water set points. As this temperature difference is reduced, the required flow of chilled water to this coil increases and the chilled-water pumping power is greater. For a given chilled-water or supply air temperature, the temperature difference is limited by the heat transfer characteristics of the coil. As this limit is approached, the required water flow and pumping power would become infinite if the pump speed were not constrained. It is generally better to have too large rather than too small a temperature difference between the supply air and chilled-water set points.

For constant chilled-water flow, tradeoffs in energy use with chilled-water set point are very different than for variable-flow systems. Increasing the chilled-water set point reduces chiller

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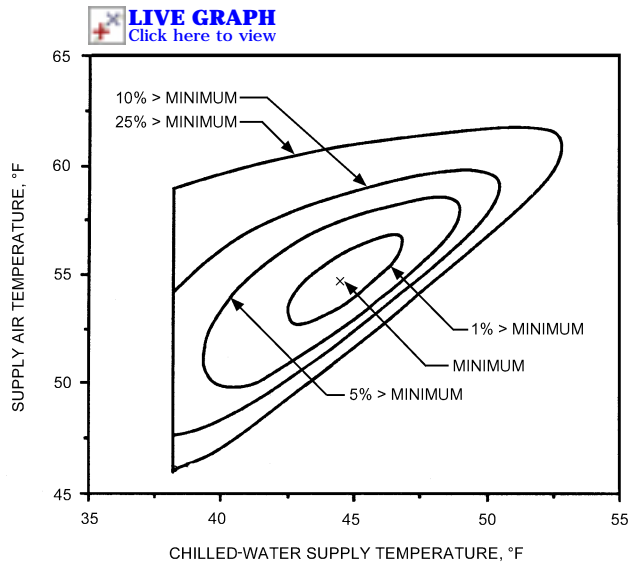
**Fig. 6   Example Power Contours for
Chilled-Water and Supply Air
Temperatures**

LIVE GRAPH
Click here to view

**Fig. 7   Example of Effect of Chiller and
Pump Sequencing on Optimal Performance**

power consumption, but has little effect on chilled-water pumping energy. Therefore, the benefits of chilled-water temperature reset are more significant than for variable-flow systems (although variable-flow systems use less energy). For constant chilled-water flow, the minimum-cost strategy is to raise the chilled-water set point to the highest value that will keep all discharge air temperatures at their set points and keep zone humidities within acceptable bounds.

For constant-volume (CAV) air-handling systems, tradeoffs in energy use with supply air set point are also very different than for variable-air-volume (VAV) systems. Increasing the supply air set point for cooling reduces both the cooling load and reheat required, but does not change fan energy. Again, the benefits of supply air temperature reset for CAV systems are more significant than for VAV systems (although VAV systems use less energy). In general, the set point for a CAV system should be the highest value that will keep all zone temperatures at their set points and all humidities within acceptable limits.

In addition to the set points used by local-loop controllers, a number of operational modes can affect performance. For instance, significant energy savings are possible when a system is properly switched over to an economizer cycle. At the onset of economizer operation, return dampers are closed, outside dampers are opened, and the maximum possible outside air is supplied to cooling coils. Two different types of switchover are typically used: (1) dry-bulb and (2) enthalpy. With a dry-bulb economizer, the switchover occurs when the ambient dry-bulb temperature is less than a specified value, typically between 55 and 65°F. With an enthalpy economizer, the switchover typically happens when the outside enthalpy (or wet-bulb temperature) is less than the enthalpy (or wet-bulb temperature) of the return air. Although the enthalpy economizer yields lower overall energy consumption, it requires wet-bulb temperature or dry-bulb and relative humidity measurements.

Another important operation mode is the sequencing of chillers and pumps. Sequencing defines the order and conditions associated with bringing equipment online or offline. Optimal sequencing depends on the individual design and part-load performance characteristics of the equipment. For instance, more-efficient chillers should generally be brought online before less-efficient ones. Furthermore, the conditions where chillers and pumps should be brought online depend on their performance characteristics at part-load conditions.
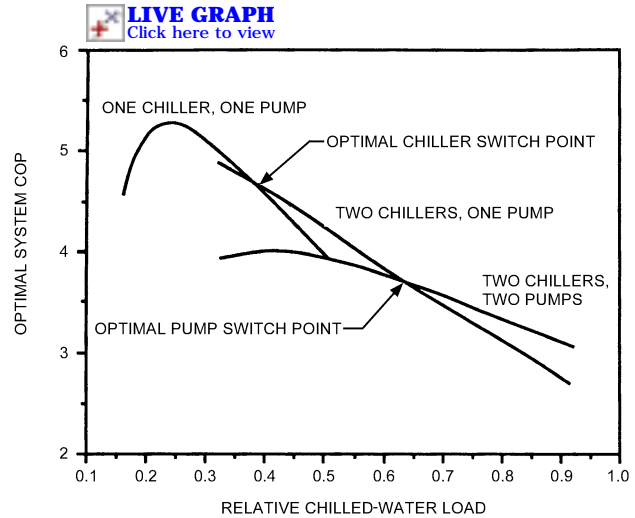
Figure 7 shows an example of optimal system performance (i.e., optimal set-point choices) for different combinations of chillers and fixed-speed pumps in parallel as a function of load relative to the design load for a given ambient wet-bulb temperature. For this system (from Braun et al. 1989a), each component (chillers, chilled-water pumps, and condenser water pumps) in each parallel set is identical and sized to meet half of the design requirements. The best performance occurs at about 25% of the design load with one chiller and pump operating. As load increases, system COP decreases because of decreasing chiller COP and a nonlinear increase in the power consumption of cooling tower and air handler fans. A second chiller should be brought online at the point where the overall COP of the system is the same with or without the chiller. For this system, this optimal switch point occurs at about 38% of the total design load, or about 75% of the individual chiller's capacity. The optimal switch point for bringing a second condenser and chilled-water pump online occurs at a much higher relative chilled load (0.62) than the switch point for adding or removing a chiller (0.38). However, pumps are typically sequenced with chillers (i.e., they are brought online together). In this case, Figure 7 shows that the optimal switch point for bringing a second chiller online (with pumps) is about 50% of the overall design load or at the design capacity of the individual chiller. This is generally the case for sequencing chillers with dedicated pumps.

In most cases, zone humidities are allowed to float between upper and lower limits dictated by comfort (see Chapter 8 of the 2005 *ASHRAE Handbook—Fundamentals*). However, VAV systems can control zone humidity and temperature simultaneously. For a zone being cooled, the equipment operating costs are minimized when the zone temperature is at the upper bound of the comfort region. However, operating simultaneously at the upper limit of humidity does not minimize operating costs. Figure 8 shows an example comparison of system COP and zone humidity associated with fixed and free-floating zone humidity as a function of the relative load (from Braun et al. 1989a). Over the range of loads, allowing the humidity to float within the comfort zone produces a lower cost and zone humidity than setting the humidity at the highest acceptable value. The largest differences occur at the highest loads. Operation with the zone at the upper humidity bound results in lower latent loads than with a free-floating humidity, but this humidity control constraint requires a higher supply air temperature, which in turn results in greater air handler power consumption. For minimum energy costs, the humidity should be allowed to float freely within the bounds of human comfort.
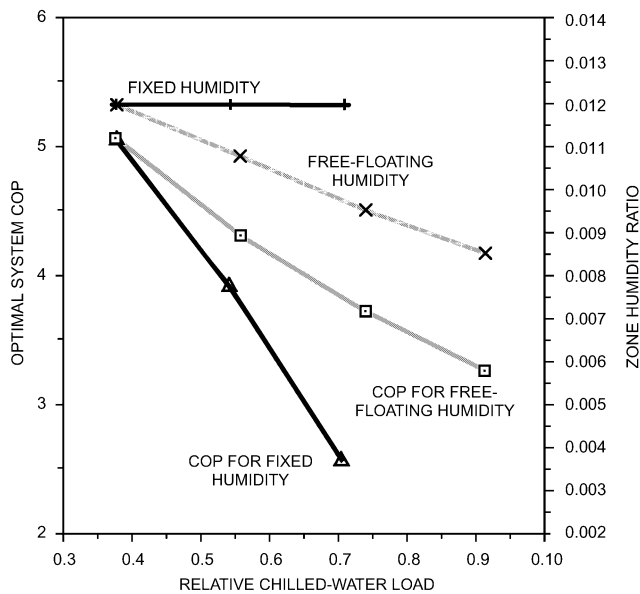
Fig. 8   Example Comparison of Free-Floating
and Fixed Humidity

Effects of Load and Ambient Conditions on Optimal Supervisory Control

When the ratio of individual zone loads to total load does not change significantly with time, the optimal control variables are functions of the total sensible and latent gains to the zones and of the ambient dry- and wet-bulb temperatures. For systems with wet cooling towers and climates where moisture is removed from conditioned air, the effect of the ambient dry-bulb temperature alone is small because air enthalpy depends primarily on wet-bulb temperature, and the performance of wet-surface heat exchangers is driven primarily by the enthalpy difference. Typically, zone latent gains are on the order of 15 to 25% of the total zone gains, and changes in latent gains have a relatively small effect on performance for a given total load. Consequently, in many cases optimal supervisory control variables depend primarily on ambient wet-bulb temperature and total chilled-water load. However, load distributions between zones may also be important if they change significantly over time.

Generally, optimal chilled-water and supply air temperatures decrease with increasing load for a fixed ambient wet-bulb temperature and increase with increasing ambient wet-bulb temperature for a fixed load. Furthermore, optimal cooling tower airflow and condenser water flow rates increase with increasing load and ambient wet-bulb temperature.

Performance Comparisons for Supervisory Control Strategies

Optimization of plant operation is most important when loads vary and when operation is far from design conditions for a significant period. Various strategies are used for chilled-water systems at off-design conditions. Commonly, the chilled-water and supply air set-point temperatures are changed only according to the ambient dry-bulb temperature. In some systems, cooling tower airflow and condenser water flow are not varied in response to changes in the load and ambient wet-bulb temperature. In other systems, these flow rates are controlled to maintain constant temperature differences between cooling tower outlet and ambient wet-bulb temperature (approach) and between cooling tower inlet and outlet (range), regardless of load and wet-bulb temperature. Although these strategies seem reasonable, they do not generally minimize operating costs.
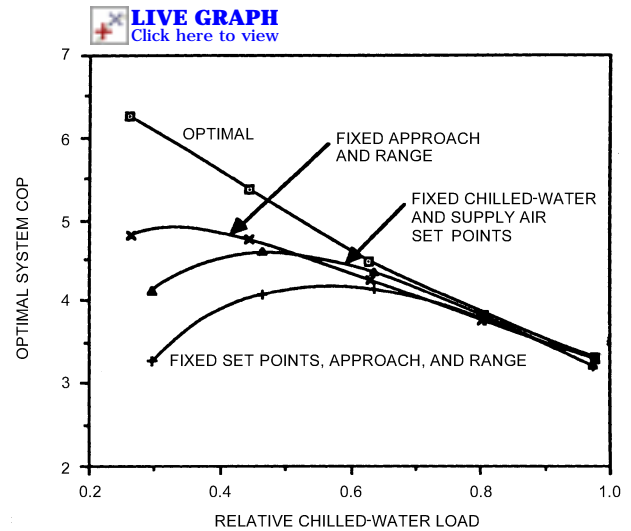
Fig. 9   Comparisons of Optimal Control with
Conventional Control Strategies

Figure 9 shows a comparison of the COPs for optimal control and three alternative strategies as a function of load for a fixed ambient wet-bulb temperature. This system (from Braun et al. 1989a) incorporated the use of variable-speed pumps and fans. The three strategies are

- Fixed chilled-water and supply air temperature set points (40 and 52°F, respectively), with optimal condenser-loop control
- Fixed tower approach and range (5 and 12°F, respectively), with optimal chilled-water loop control
- Fixed set points, approach, and range

Because the fixed values were chosen to be optimal at design conditions, the differences in performance for all strategies are minimal at high loads. However, at part-load conditions, Figure 9 shows that the savings associated with the use of optimal control can become significant. Optimal control of the chilled-water loop results in greater savings than that for the condenser loop for part-load ratios less than about 50%. The overall savings over a cooling season depend on the time variation of the load. If the cooling load is relatively constant and near the design load, fixed values of temperature set points, approach, and range could be chosen to give near-optimal performance. However, for typical building loads with significant daily and seasonal variations, the penalty for using a fixed set-point control strategy is typically in the range of 5 to 20% of the cooling system energy.

Even greater energy savings are possible with economizer control and discharge air temperature reset with constant-volume systems. Kao (1985) investigated the effect of different economizer and supply air reset strategies on both heating and cooling energy use for CAV, VAV, and dual-duct air handling systems for four different buildings. The results indicated that substantial improvements in a building's energy use may be obtained.

Variable- Versus Fixed-Speed Equipment

Using variable-speed motors for chillers, fans, and pumps can significantly reduce energy costs but can also complicate the problem of determining optimal control. The overall savings from using variable-speed equipment over a cooling season depend on the time variation of the load. Typically, using variable-speed drives reduces equipment operating costs by 20 to 50% compared to equipment with fixed-speed drives.

Figure 10 gives the overall optimal system performance for a cooling plant with either variable- or fixed-speed, variable-vane control of a centrifugal chiller. At part-load conditions, the system COP associated with using a variable-speed chiller is improved as much as
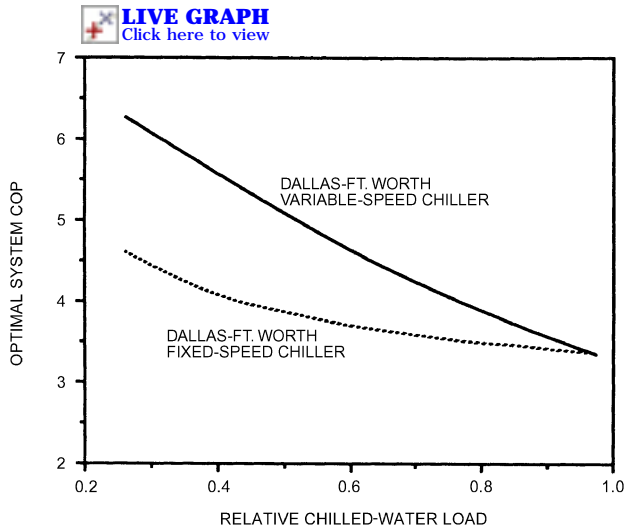
Fig. 10 Example of Optimal Performance for
Variable- and Fixed-Speed Chillers

Fig. 12 Example Comparison of Variable- and
Fixed-Speed Pumps

Fig. 11 Example Comparison of One-, Two-, and Variable-
Speed Fans for Four-Cell Cooling Tower

25%. However, the power requirements are similar at conditions associated with peak loads, because at full load the vanes are wide open and the speed under variable-speed control and fixed-speed operation is the same. The results in Figure 10 are from a single case study of a large chilled-water facility at the Dallas/Ft. Worth Airport (Braun et al. 1989a), constructed in the mid-1970s, where the existing chiller was retrofitted with a variable-speed drive. Differences in performance between variable- and fixed-speed chillers may be smaller for current equipment.

The most common design for cooling towers places multiple tower cells in parallel with a common sump. Each tower cell has a fan with one, two, or possibly three operating speeds. Although multiple cells with multiple fan settings offer wide flexibility in control, using variable-speed tower fans can further improve overall system performance. Figure 11 shows an example comparison of optimal performance for single-, two-, and variable-speed tower fans as a function of load for a given wet-bulb temperature for a system with four cells (Braun et al. 1989a). The variable-speed option results in higher COP under all conditions. In contrast, for discrete fan control, the tower cells are isolated when their fans are off and the performance is poorer. Below about 70% of full-load conditions, there is a 15% difference in total energy consumption between single-speed and variable-speed fans. Between two-speed and

variable-speed fans, the differences are much smaller, about 3 to 5% over the entire range.

Fixed-speed pumps that are sized to give proper flow to a chiller at design conditions are oversized for part-load conditions. Thus, the system will have higher operating costs than with a variable-speed pump of the same design capacity. Multiple pumps with different capacities have increased flexibility in control, and using a smaller fixed-speed pump for low loads can reduce overall power consumption. The optimal performance for variable-speed and fixed-speed pumps applied to both the condenser and chilled-water flow loops is shown in Figure 12 (Braun et al. 1989a). Large fixed-speed pumps were sized for design conditions; the small pumps were sized to have one-half the flow capacity of the large pumps. Below about 60% of full-load conditions, a variable-speed pump showed a significant improvement over the use of a single, large fixed-speed pump. With the addition of a small fixed-speed pump, improvements with the variable-speed pump were significant at about 40% of the maximum load.

Fan energy consumed by VAV systems is strongly influenced by the device used to vary the airflow. Centrifugal fans with variable-speed drives typically provide the most energy-efficient performance. Brothers and Warren (1986) compared the fan energy consumption for a typical office building in various U.S. locations. The analysis focused on centrifugal and vaneaxial fans with three typical flow modulation devices: (1) dampers on the outlet side of the fan, (2) inlet vanes on the fan, and (3) variable-speed control of the fan motor. In all locations, the centrifugal fan used less energy than the vaneaxial fan. Vaneaxial fans have higher efficiencies at the full-load design point, but centrifugal fans have better off-design characteristics that lead to lower annual energy consumption. For a centrifugal fan, inlet vane control saved about 20% of the energy compared to damper control. Variable-speed control produced average savings of 57% compared to inlet vane control.

OPTIMIZING CONTROLS FOR COOLING SYSTEMS WITH STORAGE

Using a thermal storage system allows part or all of the cooling load to be shifted from on-peak to off-peak hours. As described in Chapter 34, there are several possible storage media and system configurations. Figure 13 depicts a generic storage system coupled to a cooling system and a building load. The storage medium could be ice, chilled water, or the building structure itself (**building thermal mass**). In ice storage, the cooling equipment **charges** (operates at low temperatures to make ice) during unoccupied periods when
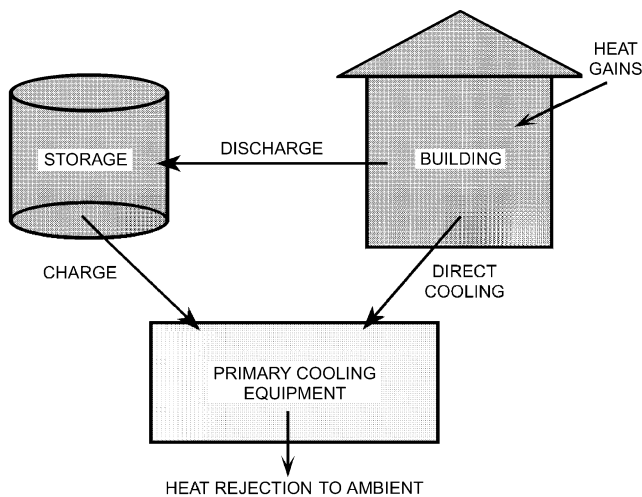
Fig. 13 Generic Storage System for Cooling

Fig. 14 Schematic of an Ice Storage System

the cost of electricity is low. During times of occupancy and higher electric rates, the ice is melted (**storage discharging**) as the storage meets part of the building load in combination with the primary cooling equipment. In building structure storage, the building is the storage medium and charging and discharging are accomplished by adjusting space temperatures over a relatively narrow range.

Utility incentives encouraging use of thermal storage are generally in the form of time-varying energy and peak demand charges. The commercial consumer is charged more for energy during the daytime and is also levied an additional charge each month based on the peak power consumption during the on-peak period. These incentives can be significant, depending on location, and are the most important factor affecting optimal control strategy for systems with thermal storage.

The primary control variables for the thermal storage systems depicted in Figure 13 are the rates of (1) energy removal from storage by the cooling system (charging rate) and (2) energy addition because of the load (discharging rate). Determining the optimal charging and discharging rates differs considerably from determining optimal set points for cooling plants that do not have storage. With thermal storage, control decisions (i.e., charging and discharging rates) determined for the current hour affect costs and control decisions for several hours in the future. Optimal control of thermal storage systems involves finding a sequence of charging and discharging rates that minimizes the total cost of providing cooling over an extended period of time, such as a day, and requires forecasting and application of dynamic optimization techniques. Constraints include limits on charging and discharging rates. The optimal control sequence results from tradeoffs between the costs of cooling the storage during off-peak hours and the cost of meeting the load during on-peak hours. In the absence of any utility incentives to use electricity at night, the optimal control generally minimizes use of storage. For an ice storage system, this is primarily because the cooling equipment operates less efficiently while charging at low temperatures. For building thermal mass systems, this is because precooling increases heat gains from the ambient to the building.

Online optimal control of thermal storage, like other HVAC optimal control schemes, is rarely implemented because of the high initial costs associated with sensors (e.g., power) and software implementation. However, heuristic control strategies have been developed that provide near-optimal performance under most circumstances. The following sections provide background on developing control strategies for ice storage and building thermal mass. Detailed descriptions of some specific control strategies are given in the Supervisory Control Strategies and Tools section of this chapter.
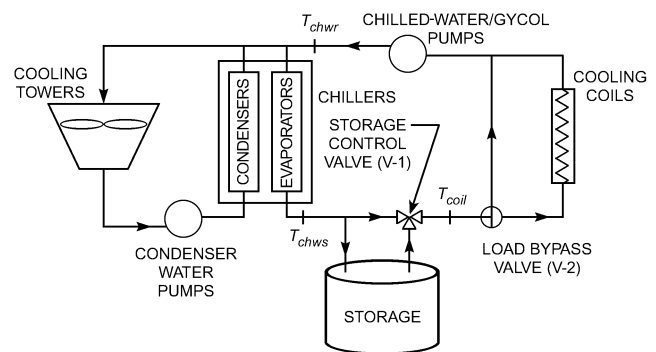
Ice Storage

This section emphasizes ice storage applications, although much of the information applies to chilled-water storage as well. Figure 14 shows a schematic of a typical ice storage system. The system consists of one or more chillers, cooling tower cells, condenser water pumps, chilled-water/glycol distribution pumps, ice storage tanks, and valves for controlling charging and discharging modes of operation. Ice is made at night and used during the day to provide part of a building's cooling requirements; the storage is not sized to handle the full on-peak load requirement on the design day. Typically, in a load-leveling scheme, the storage and chiller capacity are sized such that chiller operates at full capacity during the on-peak period on the design day.

Typical modes of operation for the system in Figure 14 are as follows:

- **Storage charging mode:** Typically, charging (i.e., ice making) only occurs when the building is unoccupied and off-peak electric rates are in effect. In this mode, the load bypass valve V-2 is fully closed to the building cooling coils, the storage control valve V-1 is fully open to the ice storage tank (the total chilled-water/glycol flow is through the tank), and the chiller produces low temperatures (e.g., 20°F) sufficient to make ice within the tank.
- **Storage discharging mode:** Discharging of storage (i.e., ice melting) only occurs when the building is occupied. In this mode, valve V-2 is open to the building cooling coils and valve V-1 modulates the mixture of flows from the storage tank and chiller to maintain a constant supply temperature to the building cooling coils (e.g., 38°F). Individual valves at the cooling coils modulate their chilled-water/glycol flow to maintain supply air temperatures to the zones.
- **Direct chiller mode:** The chiller may operate to meet the load directly without using storage during the occupied mode (typically when off-peak electric rates are in effect). In this mode, valve V-1 is fully closed with respect to the storage tank.

For a typical partial-storage system, the storage meets only a portion of the on-peak cooling loads on the design day and the chiller operates at capacity during the on-peak period. Thus, the peak power is limited by the capacity of the chiller. For off-design days, there are many different control strategies that meet the building's cooling requirements. However, each method has a different overall operating cost.

The best control strategy for a given day is a function of several factors, including utility rates, load profile, chiller characteristics, storage characteristics, and weather. For a utility rate structure that includes both time-of-use energy and demand charges, the optimal strategy can depend on variables that extend over a monthly time scale. Consider the charges typically associated with electrical use within a building. The first charge is the total cost of energy use for the building over the billing period, which is usually a month. Typically, the energy cost rate varies according to time of use, with

high rates during the daytime on weekdays and low costs at night and on weekends. The second charge, the building demand cost, is the product of the peak power consumption during the billing period and the demand cost rate for that stage. The demand cost rate can also vary with time of day, with higher rates for on-peak periods. To determine a control strategy for charging and discharging storage that minimizes utility costs for a given system, it is necessary to perform a minimization of the total cost over the entire billing period because of the demand charge. An even more complicated cost optimization results if the utility rate includes ratchet clauses, whereby the demand charge is the maximum of the monthly peak demand cost and some fraction of the previous monthly peak demand cost within the cooling season. In either case, it is not worthwhile to perform an optimization over time periods longer than those for which reliable forecasts of cooling requirements or ambient conditions could be performed (e.g., 1 day). It is therefore important to have simple control strategies for charging and discharging storage over a daily cycle.

The following control strategies for limiting cases provide further insight:

- If the demand cost rate is zero and the energy cost rate does not vary with time, minimizing cost is equivalent to minimizing total electrical energy use. In general, cooling plant efficiency is lower when it is being used to make ice than when it is providing cooling for the building. Thus, in this case, the optimal strategy for minimum energy use minimizes the use of storage. Although this may seem like a trivial example, the most common control strategy in use today for partial ice storage systems, chiller-priority control, attempts to minimize the use of storage.

- If the demand cost rate is zero but energy costs are higher during on-peak than off-peak periods, minimizing cost then involves tradeoffs between energy use and energy cost rates. For relatively small differences between on-peak and off-peak rates of less than about 30%, energy penalties for ice making typically outweigh the effect of reduced rates, and chiller-priority control is optimal for many cases. However, with higher differentials between on-peak and off-peak energy rates or with chillers having smaller charging-mode energy penalties, the optimal strategy might maximize the use of storage. A control strategy that attempts to maximize the load-shifting potential of storage is called storage-priority control; in this scheme, the chiller operates during the off-peak period to fully charge storage. During the on-peak period, storage is used to cool the building in a manner that minimizes use of the chiller(s). Partial-storage systems that use storage-priority control strategies require forecasts for building cooling requirements to avoid prematurely depleting storage.

- If only on-peak demand costs are considered, then the optimal control strategy tends to maximize the use of storage and controls the discharge of storage in a manner to always minimize the peak building power. A storage-priority, demand-minimization control strategy for partial-storage systems requires both cooling load and noncooling electrical use forecasts.

A number of control strategies based on these three simple limiting cases have been proposed for ice storage systems (Braun 1992; Drees and Braun 1996; Grumman and Butkus 1988; Rawlings 1985; Spethmann 1989; Tamblyn 1985). Braun (1992) appears to have been the first to evaluate the performance of chiller-priority and storage-priority control strategies as compared with optimal control. The storage-priority strategy was termed load-limiting control because it attempts to minimize the peak cooling load during the on-peak period. For the system considered, the load-limiting strategy provided near-optimal control in terms of demand costs in all cases and worked well with respect to energy costs when time-of-day energy charges were available. However, the scope of the study was limited in terms of the systems considered.

Krarti et al. (1996) evaluated chiller-priority and storage-priority control strategies as compared with optimal control for a wide

range of systems, utility rate structures, and operating conditions. Similar to Braun (1992), they concluded that load-limiting, storage-priority control provides near-optimal performance when there are significant differentials between on-peak and off-peak energy and demand charges. However, optimal control provides superior performance in the absence of time-of-day incentives. In general, the monthly utility costs associated with chiller-priority control were significantly higher than optimal and storage-priority control. However, without time-of-use energy charges, chiller-priority control did provide good performance for individual days when the daily peak power was less than the monthly peak. General guidance based on the work is presented by Henze et al. (2003). Drees and Braun (1996) developed a simple rule-based control strategy that combines elements of storage- and chiller-priority strategies in a way that results in near-optimal performance under all conditions. The strategy was derived from heuristics obtained through both daily and monthly optimization results for several simulated systems. A modified version of this strategy is presented in the Supervisory Control Strategies and Tools section of this chapter.

Building Thermal Mass

For conventional night setup strategies, the assumption is that building mass works to increase operating costs. A massless building would require no time for precooling or preheating and would have lower overall cooling or heating loads than an actual building. However, under proper circumstances, using a building's thermal storage for load shifting can significantly reduce operational costs, even though the total zone loads may increase.

At any given time, the cooling requirement for a space is caused by convection from internal gains (lights, equipment, and people) and interior surfaces. Because a significant fraction of the internal gain is radiated to interior surfaces, the state of a building's thermal storage and the convective coupling dictates the cooling requirement. Precooling the building during unoccupied times reduces the overall convection from exposed surfaces during the occupied period as compared with night setup control, and can reduce daytime cooling requirements. The potential for storing thermal energy in the structure and furnishings of conventional commercial buildings is significant when compared to the load requirements. Typically, internal gains are about 3 to 7 W per square foot of floor space. The thermal capacity for typical concrete building structures is approximately 2 to 4 W·h/°F per square foot of floor area. Thus, for an internal space, the energy storage can handle the load for about 1 h for every 2°F of precooling of the thermal mass.

Opportunities for reducing operating costs by using building thermal mass for cooling derive from four effects: (1) reduction in demand costs, (2) use of low-cost off-peak electrical energy, (3) reduced mechanical cooling from the use of cool nighttime air for ventilation precooling, and (4) improved mechanical cooling efficiency from increased operation at more favorable part-load and ambient conditions. However, these benefits must be balanced with the increase in total cooling requirement that occurs with precooling the thermal mass. Therefore, the savings associated with load shifting and demand reductions depend on both the method of control and the specific application.

Several simulation studies have been performed that demonstrate a substantial benefit to precooling buildings in terms of cost savings and peak cooling load reduction (Andresen and Brandemuehl 1992; Braun 1990; Rabl and Norford 1991; Snyder and Newell 1990). Possible energy savings ranged from 0 to 25%; possible reductions in total building peak electrical demand ranged from 15 to 50% compared with conventional control. The results can be sensitive to the convective coupling between the air and the thermal mass, and the mass of the furnishings may be important (Andresen and Brandemuehl 1992).

Determining the optimal set of building temperatures over time that minimizes operating costs is complex. Keeney and Braun

(1996) developed a simplified approach for determining optimal control of building thermal mass using two optimization variables for the precool period and a set of rules for the occupied period of each day. This approach significantly reduces the computation required for determining the optimal control as compared with considering hourly zone set points as optimization variables. Results of the simplified approach compared well with those of detailed optimizations for a range of systems (over 1000 different combinations of building types, weather conditions, cooling plants, and utility rates).

Morris et al. (1994) performed a set of experiments using a test facility at the National Institute of Standards and Technology (NIST) to demonstrate the potential for load shifting and load leveling when control was optimized. Two different control strategies were considered: (1) minimum cooling system energy use and (2) minimum peak cooling system electrical demand. The two strategies were implemented in the test facility and compared with night setup control. Figure 15 shows the 24 h time variation in the cooling requirement for the test facility allowed to reach a steady-periodic condition for both the minimum energy use strategy and conventional night setup control. The results indicate a significant load-shifting potential for the optimal control. Overall, the cooling requirements during the occupied period were approximately 40% less for optimal than for night setup control.

Comfort conditions were also monitored for the tests. Figure 16 gives the time variation of predicted mean vote (PMV) for the two control strategies as determined from measurements at the facility. A PMV of zero is a thermally neutral sensation, positive is too warm, and negative too cool. In the region of ±0.5, comfort is not compromised to any significant extent. Figure 16 shows that the comfort conditions were essentially identical for the two control methods during the occupied period. The space temperature, which has the dominant effect on comfort, was maintained at 75°F during the occupied period for both control methods. During the unoccupied period, the cooling system was off for night setup control and the temperature floated to warm comfort conditions. On the other hand, the optimal controller precooled the space, resulting in cool comfort conditions before occupancy. During these tests, the minimum space temperature during precooling was 68°F, and the space temperature set point was raised to 75°F just before occupancy.

Figure 17 shows the 24 h time variation in the cooling requirement for the test facility for both the minimum peak demand strategy and conventional night setup. Optimal control involved

precooling the structure and adjusting the space temperatures within the comfort zone (–0.5 < PMV < 0.5) during the occupied period to achieve the minimum demand. Although the true minimum was not achieved during the tests, the peak cooling rate during the occupied period was approximately 40% less for minimum peak demand control than for night setup control.

Morris et al. (1994) demonstrated significant savings potential for control of building thermal mass; however, they also showed that the cost savings are very sensitive to the application, operating conditions, and method of control. For example, an investigation into the effect of precooling on the on-peak cooling requirements for an existing building (which may not have been a good candidate for use of building thermal storage) showed only a 10% reduction in the cooling energy required during the occupied period, with a substantial increase in the total cooling required and no reduction in the peak cooling requirement (Ruud et al. 1990). System simulations can be used to identify (1) whether the system is a good candidate

Fig. 16   Comparison of Predicted Mean Vote (PMV) for Minimum Energy and Night Setup Control
(Morris et al. 1994)

Fig. 15   Comparison of Cooling Requirements for Minimum Energy and Night Setup Control
(Morris et al. 1994)
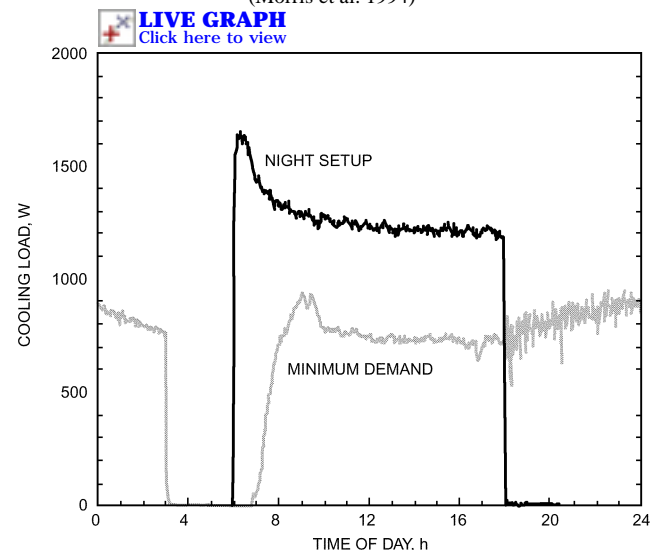
Fig. 17   Comparison of Cooling Requirements for Minimum Demand and Night Setup Control
(Morris et al. 1994)

for using building thermal mass and (2) an effective method for control, before implementing a strategy in a particular building.

Keeney and Braun (1997) used system simulation to develop a control strategy that was then tested in a large commercial building located northwest of Chicago. The goal of the control strategy was to use building thermal mass to limit the peak cooling load for continued building operation in the event of the loss of one of the four central chiller units. The algorithm was tested using two nearly identical buildings separated by a large, separately cooled entrance area. The east building used the existing building control strategy; the west building used the precooling strategy developed for this project. The precooling control strategy successfully limited the peak load to 75% of the cooling capacity for the west building, whereas the east building operated at 100% of capacity. Details of the strategy and case study results are presented in the Supervisory Control Strategies and Tools section of this chapter.

Braun et al. (2001) used on-site measurements from the same building used by Keeney and Braun (1997) to train site-specific models that were then used to develop site-specific control strategies for using building thermal mass and to evaluate the possible cost savings of these strategies. The building is an excellent candidate for using building thermal mass because it has (1) a large differential between on-peak and off-peak energy rates (about a 2-to-1 ratio), (2) a large demand charge (about $16/kW), (3) a heavy structure with significant exposed mass, and (4) cooling loads that are dominated by internal gains, leading to a high storage efficiency. The model underpredicted the total HVAC bill by about 5% but worked well enough to be used in comparing the performance of alternative control strategies.

Table 2 gives estimates of cooling-related costs and savings over the course of three summer months for different control strategies. The light precool and moderate precool strategies are simple strategies that precool the building at a fixed set point of 67°F before occupancy and then maintain a fixed discharge set point in the middle of the comfort range (73°F) during occupancy. The light precool begins at 3 AM whereas moderate precool starts at 1 AM. The extended precool strategy attempts to maintain the cooled thermal mass until the onset of the on-peak period. In this case, the set point at occupancy is maintained at the lower limit of comfort (69°F) until the on-peak period begins at 10 AM. At this point, the set point is raised to the middle of the comfort range (73°F). The other strategies use the extended precooling, but the entire comfort range is used throughout the on-peak, occupied period. The maximum discharge strategy attempts to discharge the mass as quickly as possible after the on-peak period begins. In this case, the set point is raised to the upper limit of comfort within an hour after the on-peak period begins. The slow linear rise strategy raises the set point linearly over the entire on-peak, occupied period (9 h in this case), whereas the fast linear rise strategy raises the set point over 4 h.

The strategies that do not use the entire comfort range during the occupied period (light precool, moderate precool and extended precool) all provided about 20% savings compared to night setup. Each of these strategies reduced both energy and demand costs, but the demand costs and reductions were significantly greater than the energy costs and savings. The decreases in energy costs were due to favorable on-to-off peak energy rate ratios of about 2 to 1. The high on-peak demand charges provided even greater incentives for precooling. The savings increased with the length of the precooling period, particularly when precooling was performed close to the onset of on-peak rates. The maximum discharge strategy, which maximizes discharge of the thermal storage within the structure, provided the largest savings (41%). Much of the additional savings came from reduced demand costs. The linear rise strategies also provided considerable savings with greater savings associated with faster increases in the set-point temperature.

SUPERVISORY CONTROL STRATEGIES AND TOOLS

COOLING TOWER FAN CONTROL

Figure 18 shows a schematic of the condenser loop for a typical chilled-water unit consisting of centrifugal chillers, cooling towers, and condenser water pumps. Typically, the condenser water pump control is dedicated to the chiller control to provide relatively constant flow for individual chillers. However, the cooling tower cells may be independently controlled to maximize system efficiency.

Typically, cooling tower fans are controlled using a feedback controller that attempts to maintain a temperature set point for the water supplied to the chiller condensers. Often, the condenser water supply temperature set point is held constant. However, a better strategy is to maintain a constant temperature difference between the condenser water supply and the ambient wet bulb (constant approach). Additional savings are possible through optimal control.

With a single feedback controller, the controller output signal must be converted to a specific fan sequence that depends on the number of operating cells and the individual fan speeds. Typically, with the discrete control associated with one- or two-speed tower fans, the set point cannot be realized, resulting in the potential for oscillating tower fan control. Fan cycling can be reduced by using deadbands, "sluggish" control parameters, and/or lower limits for on and off periods.

Braun and Diderrich (1990) demonstrated that feedback control for cooling tower fans could be eliminated by using an open-loop supervisory control strategy. This strategy requires only measuring

Table 2 Cooling Season Energy, Demand, and Total Costs and Savings Potential of Different Building Mass Control Strategies

Strategy	Costs in U.S. Dollars			Savings, %
	Energy	Demand	Total	
Night setup	$90,802	$189,034	$279,836	0.0
Light precool	$84,346	$147,581	$231,928	17.1
Moderate precool	$83,541	$143,859	$227,400	18.7
Extended precool	$81,715	$134,551	$216,266	22.7
Maximum discharge	$72,638	$ 91,282	$163,920	41.4
Two-hour linear rise	$72,671	$ 91,372	$164,043	41.4
Four-hour linear rise	$73,779	$115,137	$188,916	32.5
Nine-hour linear rise	$77,095	$141,124	$218,219	22.0

Source: Braun et al. (2001).
Note: Building located in Chicago, Illinois.
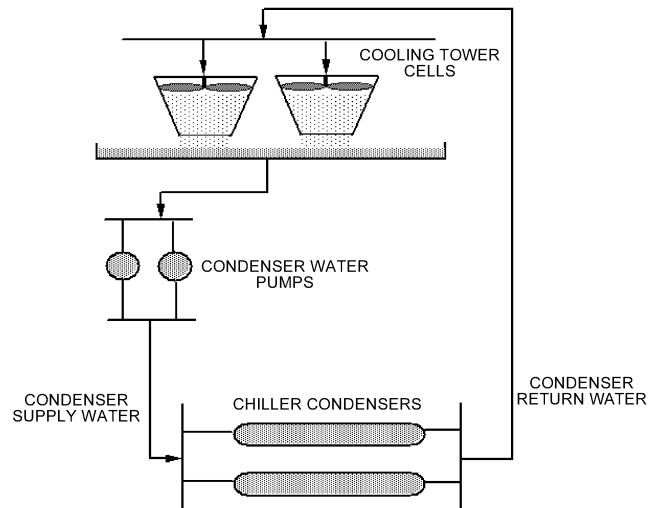
Fig. 18   Condenser Water Loop Schematic

chiller loading to specify the control and is inherently stable. The tower fan control is separated into two parts: tower sequencing and optimal airflow. For a given total tower airflow, general rules for optimal tower sequencing are used to specify the number of operating cells and fan speeds that give the minimum power consumption for both the chillers and tower fans. The optimal tower airflow is estimated with an open-loop control equation that uses design information for the cooling tower and chiller. This computational procedure is presented in this section, and the control strategy is summarized in a set of steps and sample calculations.

Near-Optimal Tower Fan Sequencing

For variable-speed fans, minimum power consumption results when all cooling tower cells are operated under all conditions. Tower airflow varies almost linearly with fan speed, whereas the fan power consumption varies approximately with the cube of the speed. Thus, for the same total airflow, operating more cells in parallel allows for lower individual fan speeds and lower overall fan power consumption. An additional benefit associated with full-cell operation is lower water pressure drops across the spray nozzles, which results in lower pumping power requirements. However, at very low pressure drops, inadequate spray distribution may adversely affect the thermal performance of the cooling tower.

Most cooling towers use multiple-speed rather than continuously adjustable variable-speed fans. In this case, it is not optimal to operate all tower cells under all conditions. The optimal number of cells operating and individual fan speeds depend on the system characteristics and ambient conditions. However, simple relationships exist for the best sequencing of cooling tower fans as capacity is added or removed. When additional tower capacity is required, Braun et al. (1989a) showed that, in almost all practical cases, the speed of the tower fan operating at the lowest speed (including fans that are off) should be increased first. The rules for bringing cell fans online are as follows:

Sequencing Rules

- **All variable-speed fans:** Operate all cells with fans at equal speeds.
- **Multiple-speed fans:** Activate lowest-speed fans first when adding tower capacity. Reverse for removing capacity.
- **Variable/multiple-speed fans:** Operate all cells with variable-speed fans at equal speeds. Activate lowest-speed fans first when adding tower capacity with multiple-speed fans. Add multiple-speed fan capacity when variable-speed fan speeds match the fan speed associated with the next multiple-speed fan increment to be added.

Similarly, for removing tower capacity, the highest fan speeds are the first to be reduced and sequences defined here are reversed.

These guidelines were derived by evaluating the incremental power changes associated with fan sequencing. For two-speed fans, the incremental power increase associated with adding a low-speed fan is less than that for increasing one to high speed if the low speed is less than 79% of the high fan speed. In addition, if the low speed is greater than 50% of the high speed, then the incremental increase in airflow is greater (and therefore thermal performance is better) for adding the low-speed fan. Most commonly, the low speed of a two-speed cooling tower fan is between one-half and three-quarters of full speed. In this case, tower cells should be brought online at low speed before any operating cells are set to high speed. Similarly, the fan speeds should be reduced to low speed before any cells are brought offline.

For three-speed fans, low speed is typically greater than or equal to one-third of full speed, and the difference between the high and intermediate speeds is equal to the difference between the intermediate and low speeds. In this situation, the best sequencing strategy is to activate the lowest fan speeds first when adding tower capacity and deactivate the highest fan speeds first when removing capacity. Typical three-speed combinations that satisfy these criteria are (1) one-third, two-thirds, and full speed or (2) one-half, three-quarters, and full speed.

Another issue related to control of multiple cooling tower cells with multiple-speed fans concerns the distribution of water flow to the individual cells. Typically, water flow is divided equally among the operating cells. Even though the overall thermal performance of the cooling tower is best when the flow is divided such that the ratio of water-to-airflow rates is identical for all cooling tower cells, equal water flow distribution results in near-optimal performance.

Near-Optimal Tower Airflow

Figure 19 illustrates the tradeoff between the chiller and cooling tower fan power associated with increasing tower airflow for variable-speed fans. As airflow increases, fan power increases with a cubic relationship. At the same time, there is a reduction in the temperature of the water supplied to the condenser of the chiller, resulting in lower chiller power consumption. The minimum total power occurs at a point where the rate of increase in fan power with airflow is equal to the rate of decrease in chiller power. Near the optimum, the total power consumption is not very sensitive to the control. This "flat" optimum indicates extreme accuracy is not needed to determine the optimum control. In general, it is better to have too high rather than too low a fan speed.

Braun et al. (1989a) showed that the tower control that minimizes the instantaneous power consumption of a cooling plant varies as a near-linear function of the load over a wide range of conditions. Although optimal control depends on the ambient wet-bulb temperature, this dependence is small compared to the load effect. Figure 20 shows an example of how the optimal tower control varies for a specific plant. The tower airflow as a fraction of the design capacity is plotted as a function of load relative to design load for two different wet-bulb temperatures. For a 20°F change in wet-bulb temperature, the optimal control varies only about 5% of the tower capacity. This difference in control results in less than a 1% difference in the plant power consumption. Figure 20 also shows that linear functions work well in correlating the optimal control over a wide range of loads for the two wet-bulb temperatures. Given the insensitivity to wet-bulb temperature and the fact that the load is highly correlated with wet bulb, a single linear relationship is adequate in correlating the optimal tower control in terms of load.

Figure 21 depicts the general form to determine tower airflow as a function of load. The (unconstrained) relative tower airflow is computed as a linear function of the part-load ratio as

$$G_{twr} = 1 - \beta_{twr} (PLR_{twr,cap} - PLR) \text{ for } 1.0 < PLR < 0.25 \quad (1)$$
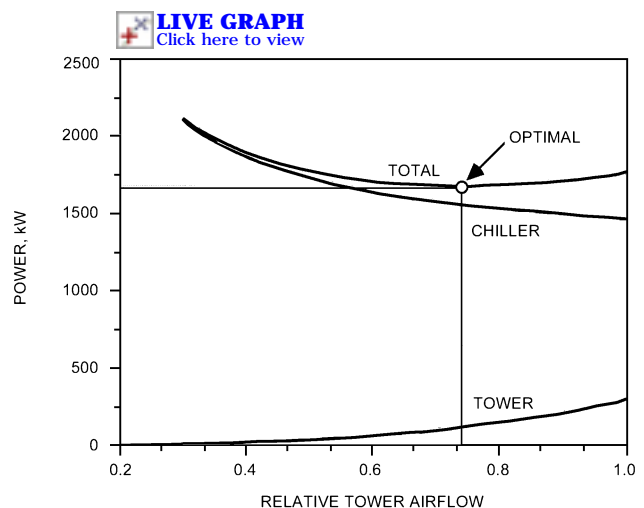
**Fig. 19 Tradeoffs Between Chiller Power and
Fan Power with Tower Airflow**

LIVE GRAPH
Click here to view
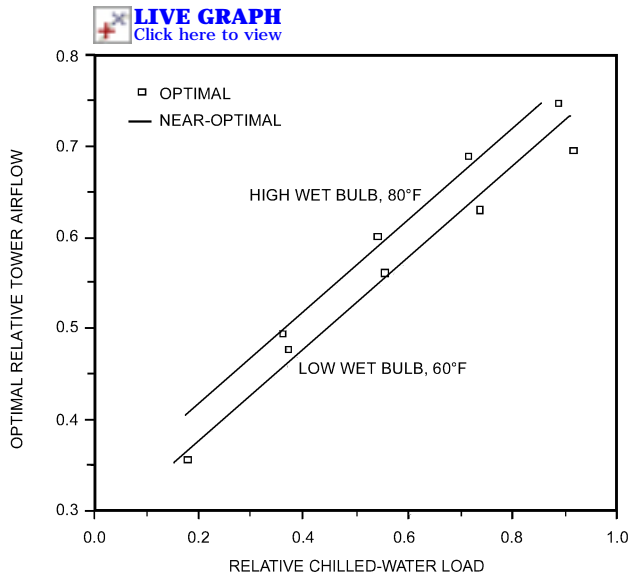
Fig. 20   Example of Optimal Tower Fan Control
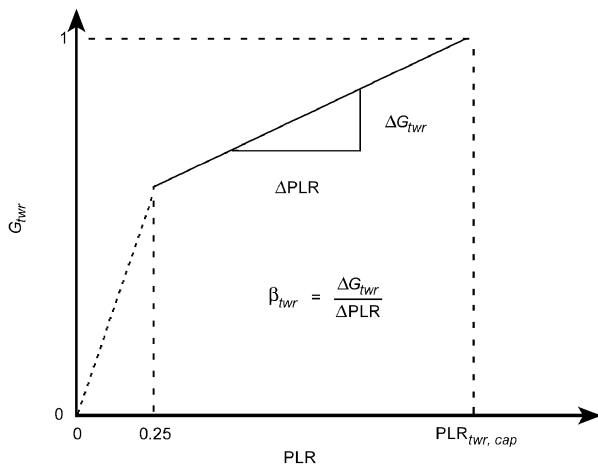
Fig. 21   Fractional Tower Airflow Versus Part-Load Ratio

where

G_{twr} = tower airflow divided by maximum airflow with all cells operating at high speed

PLR = chilled-water load divided by design total chiller plant cooling capacity (part-load ratio)

$PLR_{twr,cap}$ = part-load ratio (value of PLR) at which tower operates at its capacity (G_{twr} = 1)

β_{twr} = slope of relative tower airflow (G_{twr}) versus part-load ratio (PLR) function

The linear relationship between airflow and load is only valid for loads greater than about 25% of the design load. For many installations, chillers do not operate at these small loads. However, for those situations in which chiller operation is necessary below 25% of full load, the tower airflow should be ramped to zero as the load goes to zero according to

$$G_{twr} = 4PLR[1 - \beta_{twr}(PLR_{twr,cap} - 0.25)] \text{ for PLR} < 0.25 \quad (2)$$

The results of either Equation (1) or (2) must be constrained between 0 and 1. This fraction of tower capacity is then converted to a tower control using the sequencing rules of the section on Near-Optimal Tower Fan Sequencing.

The variables of the open-loop linear control Equation (1) that yield near-optimal control depend on the system characteristics.

Table 3   Parameter Estimates for Near-Optimal Tower Control Equation

Parameter	One-Speed Fans	Two-Speed Fans	Variable-Speed Fans
$PLR_{twr,cap}$	PLR_0	$\sqrt{2}\,PLR_0$	$\sqrt{3}\,PLR_0$
β_{twr}	$\dfrac{1}{PLR_{twr,cap}}$	$\dfrac{2}{3PLR_{twr,cap}}$	$\dfrac{1}{2PLR_{twr,cap}}$

Note:
$$PLR_0 = \frac{1}{\sqrt{\dfrac{P_{ch,des}}{P_{twr,des}}}\,S_{cwr,des}(a_{twr,des} + r_{twr,des})}$$

Detailed measurements may be taken over a range of conditions and used to accurately estimate these variables. However, this requires measuring component power consumption along with considerable time and expertise, and may not be cost effective unless performed by on-site plant personnel. Alternatively, simple estimates of these parameters may be obtained using design data.

Open-Loop Parameter Estimates Using Design Data. Good estimates for the parameters of Equation (1) may be determined analytically using design information as summarized in Table 3. These estimates were derived by Braun and Diderrich (1990) by applying optimization theory to a simplified mathematical model of the chiller and cooling tower, assuming that the tower fans are sequenced in a near-optimal manner. In general, these estimates are conservative in that they should provide greater rather than less than the optimal tower airflow. The results given in Table 3 for variable-speed fans should also provide adequate estimates for three-speed fans.

Design factors that affect the parameter estimates given in Table 3 are the (1) ratio of chiller power to cooling tower fan power at design conditions $P_{ch,des}/P_{twr,des}$, (2) sensitivity of chiller power to changes in condenser water return temperature at design conditions $S_{cwr,des}$, and (3) sum of the tower approach and range at design conditions ($a_{twr,des} + r_{twr,des}$). Chiller power consumption at design conditions is the total power consumption of all plant chillers operating at their design cooling capacity. Likewise, the design tower fan power is the total power associated with all tower cells operating at high speed. As the ratio of chiller power to tower fan power increases, it becomes more beneficial to operate the tower at higher airflows. This is reflected in a decrease in the part-load ratio at which the tower reaches its capacity, $PLR_{twr,cap}$. If the tower airflow were free (i.e., zero fan power), then $PLR_{twr,cap}$ would go to zero, and the best strategy would be to operate the towers at full capacity independent of the load. A typical value for the ratio of the chiller power to the cooling tower fan power at design conditions is 10.

The chiller sensitivity factor $S_{cwr,des}$ is the incremental increase in chiller power for each degree increase in condenser water temperature as a fraction of the power or

$$S_{cwr,des} = \frac{\text{Change in chiller power}}{\text{Change in cond. water return temp.} \times \text{Chiller power}} \quad (3)$$

If the chiller power increases by 2% for a 1°F increase in condenser water temperature, $S_{cwr,des}$ is equal to 0.02/°F. A large sensitivity factor means that the chiller power is very sensitive to the cooling tower control favoring operation at higher airflow rates (low $PLR_{twr,cap}$). The sensitivity factor should be evaluated at design conditions using chiller performance data. Typically, the sensitivity factor is between 0.01 and 0.03/°F. For multiple chillers with different performance characteristics, the sensitivity factor at design conditions is estimated as

$$S_{cwr,des} = \frac{\sum_{i=1}^{N_{ch}} S_{cwr,des,i} P_{ch,des,i}}{\sum_{i=1}^{N_{ch}} P_{ch,des,i}} \qquad (4)$$

where $S_{cwr,des,i}$ is the sensitivity factor and $P_{ch,des,i}$ is the power consumption for the ith chiller at the design conditions, and N_{ch} is the total number of chillers.

The design approach to wet bulb $a_{twr,des}$ is the temperature difference between the condenser water supply and the ambient wet bulb for the tower, operating at its air and water flow capacity at plant design conditions. The design range $r_{twr,des}$ is the water temperature difference across the tower at these same conditions (condenser water return minus supply temperature). The sum of $a_{twr,des}$ and $r_{twr,des}$ is the temperature difference between the tower inlet and ambient wet bulb, and represents a measure of the tower's capability to reject heat to ambient relative to the system requirements. A small temperature difference (tower approach plus range) results from a high tower heat transfer effectiveness or high water flow rate and yields lower condenser water temperatures with lower chiller power consumption. Typical values for the design approach and range are 7 and 10°F.

The part-load ratio associated with the tower operating at full capacity, $PLR_{twr,cap}$ may be greater than or less than one. Values less than unity imply that, from an energy point of view, the tower is not sized for optimal operation at design load conditions and that it should operate at its capacity for a range of loads less than the design load. Values of $PLR_{twr,cap}$ greater than one imply that the tower is oversized for the design load and that it should never operate at its capacity.

For multiple chillers with very different performance characteristics, different open-loop parameters may be used for any combination of operating chillers. The sensitivity factors and chiller design power used to determine the open-loop control parameters in Table 3 should be estimated for each combination of operating chillers, and the part-load ratio used in Equation (1) should be determined using the design capacity for the operating chillers (not all chillers). In this case, N_{ch} in Equation (4) represents the number of operating chillers.

Open-Loop Parameter Estimates Using Plant Measurements. Energy consumption can be reduced slightly by determining the open-loop control parameters from plant measurements. However, this results in additional complexity associated with implementation. One method for estimating the open-loop control parameters of Equation (1) from plant measurements involves performing a set of one-time trial-and-error experiments. At a given set of conditions (i.e., cooling load and ambient conditions), the optimal tower control is estimated by varying the fan settings and monitoring the total chiller and fan power consumption. Each tower control setting and load condition must be maintained for a sufficient time for the power consumption to approach steady-state and to hold the chilled-water supply temperature constant. The control setting that produces the minimum total power consumption is deemed optimal. This set of experiments is performed for a number of chilled-water cooling loads and the best-fit straight line through the resulting data points is used to estimate the parameters of Equation (1). As initial control settings for each load, Equation (1) may be used with estimates from design data as summarized in the previous section.

Another method for estimating the variables of Equation (1) uses an empirical model for total power consumption that is fit to plant measurements. The control that minimizes the power consumption associated with the model is then determined analytically. The section on Control Optimization Methods describes a general method for determining linear control relations in this manner using a quadratic model. For cooling tower fan control, chiller and fan power consumption are correlated with load and tower airflow for a constant chilled-water supply temperature using a quadratic function as follows:

$$\begin{aligned} P = {}& a_0 + a_1 PLR + a_2 PLR^2 + a_3 G_{twr} \\ & + a_4 G_{twr}^2 + a_5 PLR \times G_{twr} \end{aligned} \qquad (5)$$

where a_0 to a_5 are empirical constants determined through linear regression applied to measurements. For the quadratic function of Equation (5), the tower airflow that results in minimum power is a linear function of the PLR. The parameters of the open-loop control Equation (1) are then

$$PLR_{twr,cap} = -\frac{a_3 + 2a_4}{a_5} \qquad (6)$$

$$\beta_{twr} = -\frac{a_5}{2a_4} \qquad (7)$$

For multiple chillers with very different performance characteristics, different open-loop parameters can be determined for any combination of operating chillers. In this case, separate correlations for near-optimal airflow or power consumption must be determined for each chiller combination.

Overrides for Equipment Constraints

The fractional tower airflow as determined by Equations (1) or (2) must be bounded between 0 and 1 according to the physical constraints of the equipment. Additional constraints on the temperature of the supply water to the chiller condensers are necessary to avoid potential chiller maintenance problems. Many (older) chillers have a low limit on the condenser water supply temperature that is necessary to avoid lubrication migration from the compressor. A high-temperature limit is also necessary to avoid excessively high pressures in the condenser, which can lead to compressor surge in centrifugal chillers. If condenser water temperature falls below the low limit, then it is necessary to override the open-loop tower control and reduce tower airflow to go above this limit. Similarly, if the high limit is exceeded, then the tower airflow should be increased as required.

Implementation

Before commissioning, the parameters of the open-loop control Equation (1) must be specified. These parameters are estimated using Table 3. After the system is in operation, these parameters may be fine-tuned with measurements as outlined previously. If multiple chillers have significantly different performance characteristics, it may be advantageous to determine different parameters for Equation (1) depending on the combination of operating chillers.

The relative tower airflow must be converted to a specific set of tower fan settings using the sequencing rules defined previously. This involves defining a relationship (i.e., table) for fan settings as a function of tower airflow. The table is constructed by defining the best fan settings for each possible increment of airflow. The conversion process between the continuous output of Equations (1) or (2) and the fan control involves choosing the set of discrete fan settings from the table that produces a tower airflow closest to the desired flow. However, in general, it is better to have greater rather than less than the optimal airflow. A good general rule is to choose the set of discrete fan controls that results in a relative airflow that is closest to, but not more than 10% less than, the output of Equations (1) or (2).

With the parameters of Equation (1) specified, the following procedure is applied at each decision interval (e.g., 15 min) to determine the tower control:

1. If the temperature of supply water to the chiller condenser is less than the low limit, then reduce tower airflow by one increment according to the near-optimal sequencing rules and exit the algorithm. Otherwise go to step 2.
2. If the temperature of supply water to the chiller condenser is greater than the high limit, then increase tower airflow by one increment according to the near-optimal sequencing rules and exit the algorithm. Otherwise go to step 3.
3. Determine the chilled-water load relative to the design load.
4. If the chilled-water load has changed by a significant amount (e.g., 10%) since the last control change, then go to step 5. Otherwise exit the algorithm.
5. If the part-load ratio is greater than 0.25, then compute the near-optimal tower airflow as a fraction of tower capacity G_{twr} with Equation (1). Otherwise, determine G_{twr} with Equation (2).
6. Limit G_{twr} to keep the change from the previous decision interval less than a minimum value (e.g., less than 0.1 change).
7. Restrict the value of G_{twr} between 0 and 1.
8. Convert the value of G_{twr} to a specific set of control functions for each of the tower cell fans according to the near-optimal sequencing rules.

This procedure requires some estimate of the chilled-water load, along with a measurement of the condenser water supply temperature. However, accuracy of the load estimates is not extremely critical. In general, near-optimal control determined with load estimates that are accurate to within 5 to 10% results in total power consumption that is within 1% of the minimum. The best method for determining the chilled-water load is from the product of the measured chilled-water flow rate and the temperature difference between the chilled-water return and supply. For systems that use constant flow pumping to the chillers, the flow rates may be estimated from design data for the pumps and system pressure-drop characteristics.

Example 1. Consider an example plant consisting of four 550 ton chillers with four cooling tower cells, each having two-speed fans. Each chiller consumes approximately 330 kW at the design capacity, and each tower fan uses 40 kW at high speed. At design conditions, the chiller power increases approximately 6.6 kW for a 1°F increase in condenser water temperature, giving a sensitivity factor of 6.6/330 or 0.02/°F. The tower design approach and range from manufacturer's data are 7 and 10°F.

Solution:
The first step in applying the open-loop control algorithm to this problem is determining the parameters of Equation (1) from the design data. From Table 3, the part-load ratio at which operation of the tower is at its capacity is estimated for the two-speed fans as

$$\text{PLR}_{twr,cap} = \frac{1}{\sqrt{\frac{1}{2}(0.02/°F)\frac{4 \times 330 \text{ kW}}{4 \times 40 \text{ kW}}(7 + 10°F)}} = 0.84$$

and the slope of the fractional airflow versus part-load ratio is estimated to be

$$\beta_{twr} = \frac{2}{3 \times 0.84} = 0.79$$

Given these parameters and the part-load ratio, the fractional tower airflow is estimated as

IF (PLR > 0.25) THEN

$$G_{twr} = 1 - \beta_{twr}(\text{PLR}_{twr,cap} - \text{PLR})$$

ELSE

$$G_{twr} = 4\text{PLR}[1 - \beta_{twr}(\text{PLR}_{twr,cap} - 0.25)]$$

$$G_{twr} = \text{MIN}[1, \text{MAX}(0, G_{twr})]$$

To convert G_{twr} into a specific tower control, the tower sequencing must be defined. The following table gives this information in a form that specifies the relationship between G_{twr} and tower control for this example.

Cooling Tower Fan Sequencing for Example 1

Sequence No.	G_{twr}	Tower Fan Speeds			
		Cell #1	Cell #2	Cell #3	Cell #4
1	0.125	Low	Off	Off	Off
2	0.250	Low	Low	Off	Off
3	0.375	Low	Low	Low	Off
4	0.500	Low	Low	Low	Low
5	0.625	High	Low	Low	Low
6	0.750	High	High	Low	Low
7	0.875	High	High	High	Low
8	1.000	High	High	High	High

For a specific chilled-water load, the fan control should be the sequence of tower fan settings from the table that results in a value of G_{twr} that is closest to, but not more than 10% less than, the output of Equations (1) or (2). Note that this example assumes that proper water flow can be maintained over all cooling tower cells.

CHILLED-WATER RESET WITH FIXED-SPEED PUMPING

Figure 22 shows a common configuration using fixed-speed chilled-water pumps with two-way valves at the cooling coils. A two-way bypass valve controlled to maintain a fixed pressure difference between the main supply and return lines is used to ensure relatively constant flow through chiller evaporators and reduce pressure drop and pumping costs at low loads. However, pump and chiller power savings can be increased by adjusting the chilled-water supply temperature to keep some cooling coil valves open and thereby minimize the bypass flow.

Ideally, the chilled-water temperature should be adjusted to maintain all discharge air temperatures with a minimal number of cooling-coil control valves in a saturated (fully open) condition. The procedure described in this section is designed to accomplish this goal in a reliable and stable manner that reacts quickly to changing conditions.

Pump Sequencing

Individual chilled-water pumps are commonly physically dedicated to individual chillers. In this case, the sequencing of chilled-water pumps is defined by the sequencing of chillers. In some installations, the chiller pumps are not dedicated to chillers, but instead are arranged in parallel, sharing common headers. In this case, the order for bringing pumps online and offline and the conditions for
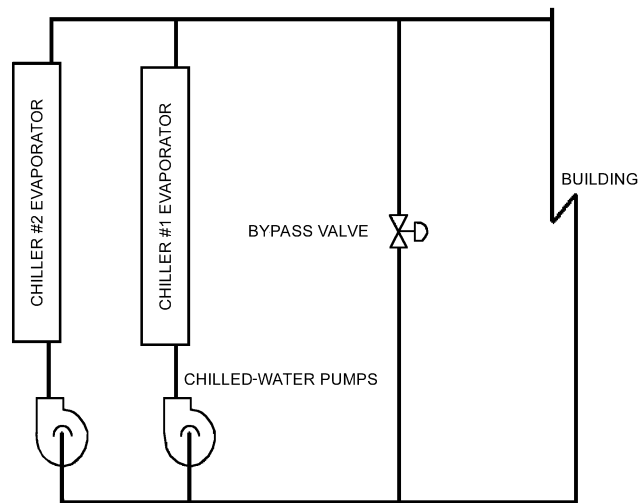
Fig. 22 Typical Chilled-Water Distribution for Fixed-Speed Pumping

adding or removing chilled-water pump capacity must be specified. For pumps of different capacities, the logical order for bringing pumps online is from small to large. For pumps of similar capacity, the most efficient pumps should be brought online first and taken offline last.

Optimal Chilled-Water Temperature

One method for determining the optimal chilled-water temperature is to monitor the water control valve positions of "representative" air handlers and to adjust the set temperature incrementally at fixed decision intervals until a single control valve is fully open. The representative air handlers should be chosen to include load diversity at all times and ensure reliable data. One difficulty of this control approach is that valve position data are often unreliable. The valve could be stuck open, or the saturation indicator could be faulty. This problem can be overcome by also monitoring discharge air temperatures, using them as a consistency check on valve position data. If a valve is unsaturated, this implies that the coil has sufficient capacity to maintain the discharge air temperature near the set point. Conversely, if a valve remains saturated at 100% open, the discharge air temperature should ultimately increase above the set point. These considerations lead to the following simple rules for increasing or decreasing the chilled-water set point in response to valve position and discharge air temperature data.

- If all water valves are unsaturated or the discharge air temperatures associated with all saturated valves are lower than the set point, increase the chilled-water set temperature.
- If more than one valve is saturated at 100% open and their corresponding discharge air temperatures are greater than their set points, decrease the chilled-water temperature.

In implementing these rules, a fixed increment for increasing or decreasing the chilled-water temperature must be chosen. A small increment results in more stable control, but also results in a slow response to sudden changes in load or supply air temperature set points. Using a first-order approximation, the chilled-water temperature can be reset in response to sudden changes in load and supply air temperature set point according to

$$t_{chws} = t_{as} - \frac{\text{PLR}}{\text{PLR}_o}(t_{as,o} - t_{chws,o}) \qquad (8)$$

where

t_{chws} = new chilled-water set-point temperature
t_{as} = current supply air set-point temperature
PLR = current part-load ratio (chiller load divided by total design load for all chillers)
$t_{chws,o}$ = chilled-water set point associated with last control decision
$t_{as,o}$ = supply air set point associated with last control decision
PLR_o = part-load ratio associated with last control decision

Equation (8) assumes that the chilled-water temperature associated with the last control decision was optimal. As a result, it only applies to anticipating the effects of significant changes in the load and supply air set-point temperature on the optimal chilled-water set point. The "bump-and-wait" strategy fine-tunes the chilled-water supply temperature when the load and supply air set point are stable. For a variable-air-volume system, the supply air set points are most often constant and identical for all air-handling units. However, for a constant-air-volume system, these set points may vary with different air handlers. In this case, the supply air set point to use in Equation (8) should be an average value for the representative air handlers.

Equation (8) indicates that the optimal chilled-water supply temperature increases with increasing supply air temperature and decreasing load. This is because these changes cause the cooling-coil valves to close; optimal control involves keeping at least one valve open. Increasing supply air temperature causes the cooling-coil

valves to close somewhat because of a larger average temperature difference for heat transfer between the water and air. A lower load requires smaller air-to-water temperature differences, which also leads to control valves closing.

Overrides for Equipment and Comfort Constraints

For a given chiller load, the chilled-water temperature has both upper and lower limits. The lower limit is necessary to avoid ice formation on the evaporator tubes of the chiller. This limit depends primarily on the load in relation to the size of the evaporator or, in other words, the temperature difference between the chilled water and refrigerant. At small temperature differences (large area or small load), the evaporator can tolerate a lower chilled-water temperature to avoid freezing than at large temperature differences. The lower limit on the chilled-water set point should be evaluated at the design load, because the overall system performance is improved by increasing chilled-water temperature above this limit for loads less than design. This lower limit can range from 38 to 44°F.

An upper limit on the chilled-water temperature arises from comfort constraints associated with the zones and the possibility of microbial growth associated with high humidities. For the available flows, the chilled-water temperature should be low enough to provide discharge air at a temperature and humidity sufficient to maintain all zones in the comfort region and avoid microbial growth. This upper limit varies with both load and entering air conditions and is accounted for by monitoring the zone conditions to ensure that they are in the comfort zone. If zone temperatures or humidities are not within reasonable bounds, then the discharge air temperature set point should be lowered.

Implementation

At each decision interval (e.g., 5 min), the following algorithm would be applied for determining the optimal chilled-water set-point temperature:

1. Determine the time-averaged total chilled-water load for the previous decision interval.
2. If the chilled-water load or supply air set-point temperature has changed by a significant amount (e.g., 10%) since the last control change, then estimate a new optimal chilled-water set point with Equation (8) and go to step 6. Otherwise, go to step 3.
3. Determine the time-averaged position of (or controller output for) the cooling-coil water valves and corresponding discharge air temperatures for representative air handlers.
4. If more than one valve is saturated at 100% open and their corresponding supply air temperatures are greater than set point (e.g., 1°F), then decrease the chilled-water temperature by a fixed amount (e.g., 0.5°F) and go to step 6. Otherwise, go to step 5.
5. If all water valves are unsaturated or the supply air temperatures associated with all valves that are saturated are lower than the set point, then raise the chilled-water set temperature by a fixed amount (e.g., 0.5°F). Otherwise, exit the algorithm with the chilled-water set point unchanged.
6. Limit the chilled-water set-point temperature between the upper and lower limits dictated by comfort, humidity, and equipment safety.

Implementing this algorithm requires some estimate of the chilled-water load, along with a measurement of the discharge air temperatures and control valve positions. However, a highly accurate estimate of the load is not necessary.

CHILLED-WATER RESET WITH VARIABLE-SPEED PUMPING

Figure 23 shows a common configuration for systems using variable-speed chilled-water pumps with primary/secondary water loops. The primary pumps are fixed speed and are generally
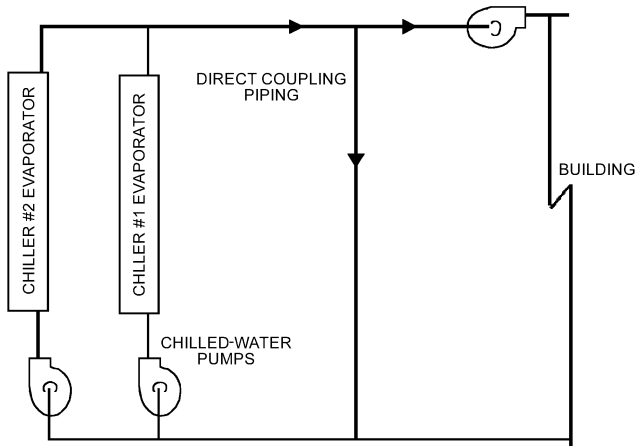
Fig. 23 Typical Chilled-Water Distribution for Primary/Secondary Pumping

Fig. 24 Tradeoff of Chiller and Pump Power with Chilled-Water Set Point

Fig. 25 Comparisons of Optimal Chilled-Water Temperature

sequenced with chillers to provide a relatively constant flow of water through the chiller evaporators. The secondary chilled-water pumps are variable speed and are typically controlled to maintain a specified set point for pressure difference between supply and return flows for the cooling coils.

Although variable-speed pumps are usually used with primary/ secondary chilled-water loops, they may also be applied to systems with a single chilled-water loop. In either case, variable-speed pumps offer the potential for a significant operating cost saving when both chilled-water and pressure differential set points are optimized in response to changing loads. This section presents an algorithm for determining near-optimal values of these control variables.

Optimal Differential Pressure Set Points

In practically all variable-speed chilled-water pumping applications, pump speed is controlled to maintain a constant pressure differential between the main chilled-water supply and return lines. However, this approach is not optimal. To maintain a constant pressure differential with changing flow, the control valves for the air-handling units must close as the load (i.e., flow) is reduced, resulting in an increase in the flow resistance. The best strategy for a given chilled-water set point is to reset the differential pressure set point to maintain all discharge air temperatures with at least one control valve in a saturated (fully open) condition. This results in a relatively constant flow resistance and greater pump savings at low loads. With variable differential pressure set points, optimizing the chilled-water loop is described in terms of finding the chilled-water temperature that minimizes the sum of the chiller and pumping power, with pump control dependent on the set point and load.

Near-Optimal Chilled-Water Set Point

The optimal chilled-water supply temperature at a given load results from a tradeoff between chiller and pumping power, as illustrated in Figure 24. As the chilled-water temperature increases, the chiller power is reduced due to a reduction in the lift requirements of the chiller. For a higher set temperature, more chilled-water flow is necessary to meet the load requirements, and the pumping power requirements increase. The minimum total power occurs at a point where the rate of increase in pumping power with chilled-water temperature is equal to the rate of decrease in chiller power. This optimal set point moves to lower values as the load increases.

Braun et al. (1989a) demonstrated that the optimal chilled-water set point varies as a near-linear function of both load and wet-bulb temperature over a wide range of conditions. Figure 25 shows an example of how the optimal set point varies for a specific plant. The
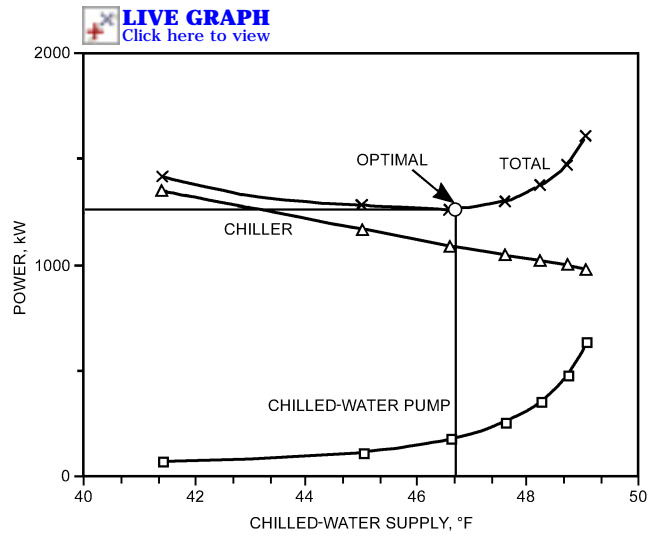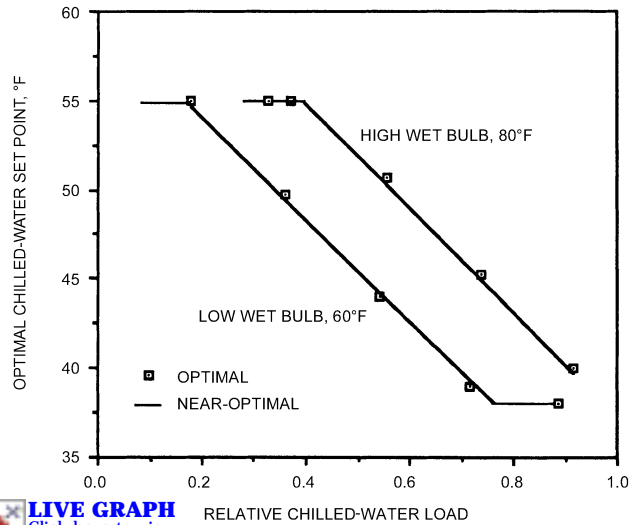
set point is plotted as a function of load relative to design load for two different wet-bulb temperatures. In general, the optimal chilled-water temperature decreases with load because the pump power becomes a larger fraction of the total power. A lower set point limit is set to avoid conditions that could form ice on evaporator tubes or too high a chiller "lift," and an upper limit is established to ensure adequate cooling-coil dehumidification. For a given load, the chilled-water set point increases with wet-bulb temperature, because energy transfer across each cooling coil is proportional to the difference between its entering air wet-bulb temperature and the entering water temperature (the chilled-water set point). For a constant load, this temperature difference is constant and the chilled-water supply temperature increases linearly with entering air wet-bulb temperature.

The results in Figure 25 were obtained for a system where both the chilled-water supply and supply air set points to the zones were optimized. For this case, the supply air temperatures varied between 55°F at high loads and 60°F at low loads. More typically, supply air temperatures are constant at 55°F, and the variation in chilled-water supply temperature is smaller than that shown in Figure 25.

Figure 26 depicts the general form for an algorithm to determine chilled-water supply set points as a function of load and the average
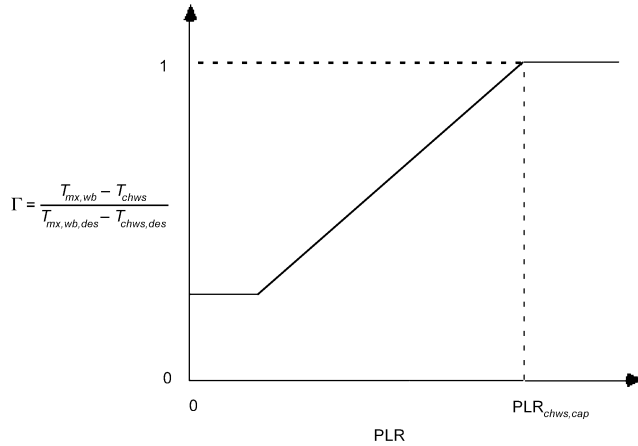
**Fig. 26   Dimensionless Chilled-Water Set Point
Versus Part-Load Ratio**

wet-bulb temperature entering the cooling coils. A normalized difference between the entering air wet-bulb temperature and the chilled-water supply temperature is shown as a linear function of the part-load ratio. The (unconstrained) chilled-water set point is determined as

$$t_{chws} = t_{mx,wb} - \Gamma(t_{mx,wb,des} - t_{chws,des}) \qquad (9)$$

where

$$\Gamma = 1 - \beta_{chws}(\text{PLR}_{chws,cap} - \text{PLR}) \qquad (10)$$

t_{chws} = chilled-water supply temperature set point
$t_{mx,wb}$ = average or "representative" wet-bulb temperature of air entering
    cooling coils
$t_{chws,des}$ = chilled-water supply temperature at design conditions
$t_{mx,wb,des}$= wet-bulb temperature of air entering cooling coils at design
    conditions
PLR = chilled-water load divided by the total chiller cooling capacity
    (part-load ratio)
$\text{PLR}_{chws,cap}$= part-load ratio (value of PLR) at which $\Gamma = 1$
β_{chws} = slope of the Γ versus part-load ratio (PLR) function

The result of Equation (9) must be constrained between upper and lower limits dictated by equipment safety (evaporator freezing), the machine operating envelope, and comfort and humidity concerns.

The variables of Equation (10) that yield near-optimal control depend on the system characteristics. Detailed measurements over a range of conditions may be used to determine estimates of these parameters. However, this requires measuring component power consumption along with considerable time and expertise, and may not be cost effective unless performed by on-site plant personnel. Alternatively, simple estimates of these parameters may be obtained using design data.

Open-Loop Parameter Estimates Using Design Data. Reasonable estimates of the parameters of Equation (10) may be determined analytically using design information as summarized in Table 4. These estimates were derived by applying optimization theory to a simplified mathematical model of the chiller and secondary-loop water pumps, assuming that a differential pressure reset strategy is used, pump efficiencies are constant, and the supply air temperature is not varied in response to changes in chilled-water supply temperature. In general, these parameter estimates are conservative in that they should provide a relatively low estimate of the optimal chilled-water set point.

The design factors that affect the parameter estimates given in Table 4 are the (1) ratio of the chiller power to chilled-water pump power at design conditions $P_{ch,des}/P_{chwp,des}$, (2) chiller power's sensitivity to changes in chilled-water temperature at design conditions $S_{chws,des}$, and (3) difference between design entering air wet-bulb

**Table 4   Parameter Estimates for Near-Optimal
Chilled-Water Set Point Equation**

Parameter	Estimate
$\text{PLR}_{chws,cap}$	$\sqrt{\dfrac{1}{3} \times \dfrac{P_{ch,des}}{P_{chwp,des}} S_{chws,des}(t_{mx,wb,des} - t_{chws,des})}$
β_{chws}	$\dfrac{0.5}{\text{PLR}_{chws,cap}}$

temperature to the cooling coil and the chilled-water supply temperature $(t_{mx,wb,des} - t_{chws,des})$.

Chiller power consumption at design conditions is the total power consumption of all plant chillers operating at their design cooling capacity. Likewise, the design pump power is the total power associated with all secondary chilled-water supply pumps operating at high speed. As the ratio of chiller power to pump power increases, it becomes more beneficial to operate the chillers at higher chilled-water temperatures and the pumps at higher flows. This is reflected in an increase in $\text{PLR}_{chws,cap}$. If chiller power were free, then $\text{PLR}_{chws,cap}$ would go to zero, and the best strategy would be to operate the chillers at the minimum possible set point, resulting in low chilled-water flow rates. Typical values for the ratio of chiller power to pump power at design conditions are between 10 and 20, depending primarily on whether primary/secondary pumping is used.

Chiller sensitivity factor $S_{chws,des}$ is the incremental increase in chiller power for each degree decrease in chilled-water temperature as a fraction of the power:

$$S_{chws,des} = \frac{\text{Increase in chiller power}}{\text{Decrease in chilled-water temp.} \times \text{Chiller power}} \qquad (11)$$

If chiller power increases by 2% for a 1°F decrease in chilled-water temperature, then $S_{chws,des}$ is equal to 0.02/°F. A large sensitivity factor means that chiller power is very sensitive to the set point control, favoring operation at higher set-point temperatures and flows (higher $\text{PLR}_{chws,cap}$). The sensitivity factor should be evaluated at design conditions using chiller performance data. Typically, the sensitivity factor is between 0.01 and 0.03/°F. For multiple chillers with different performance characteristics, the sensitivity factor at design conditions is estimated as

$$S_{chws,des} = \frac{\displaystyle\sum_{i=1}^{N_{ch}} S_{chws,des,i} P_{ch,des,i}}{\displaystyle\sum_{i=1}^{N_{ch}} P_{ch,des,i}} \qquad (12)$$

where $S_{chws,des,i}$ is the sensitivity factor and $P_{ch,des,i}$ is the power consumption for the ith chiller at design conditions, and N_{ch} is the total number of chillers.

The design difference between coil inlet air wet-bulb temperature and entering water temperature should be evaluated for a typical air handler operating at design load and flows. A small temperature difference results from a high coil heat transfer effectiveness or high water flow rate, allowing higher chilled-water temperatures with lower chiller power consumption. This is evident from Equation (9), where chilled-water set point decreases linearly with $(t_{mx,wb,des} - t_{chws,des})$ for a given Γ, and Γ is inversely related to the square root of $(t_{mx,wb,des} - t_{chws,des})$. Typically, this temperature difference is about 20°F.

Example 2. Consider an example plant with primary/secondary chilled-
    water pumping. There are four 550 ton chillers, each with a dedicated
    primary pump. Each chiller consumes approximately 330 kW at design

capacity. At design conditions, chiller power increases approximately 6.6 kW for a 1°F decrease in chilled-water temperature, giving a sensitivity factor of 6.6/330 or 0.02/°F. The design chilled-water set point is 42°F, and the coil entering wet-bulb temperature is 62°F at design conditions. The secondary loop uses three identical 60 hp chilled-water pumps: one with a variable-speed and two with fixed-speed motors.

Solution:

The first step in applying the open-loop control algorithm to this problem is the determination of the parameters of Equation (10) from the design data. From Table 4, the part-load ratio at which the chilled-water temperature reaches a minimum (with the design entering wet-bulb temperature to the coils) is

$$\text{PLR}_{chws,cap} = \sqrt{\frac{1}{3} \times \frac{4 \times 330 \text{ kW}}{3 \times 60 \text{ hp} \times 0.75 \text{ kW/hp}} (0.02/°F)(20°F)}$$
$$= 1.14$$

and the slope of the set point versus part-load ratio is estimated to be

$$\beta_{chws} = \frac{0.5}{1.14} = 0.44$$

Given these parameters and the part-load ratio, the unconstrained chilled-water set-point temperature from Equations (9) and (10) is then

$$t_{chws} = t_{mx,wb} - [1 - 0.44(1.14 - \text{PLR})]20$$

Pump Sequencing

Variable-speed pumps are sometimes used in combination with fixed-speed or other variable-speed pumps. Pump sequencing involves determining both the order and point that pumps should be brought online and offline.

Pumps should be brought online in an order that allows a continuous variation in flow rate and maximized operating efficiency of the pumps at each switch point for the specific pressure loss characteristic. For a combination of fixed- and variable-speed pumps, at least one variable-speed pump should be brought online before any fixed-speed pumps. For single-loop systems (i.e., no secondary loop) with variable-speed pumps, the pressure drop characteristics change when chillers are added or removed, and the optimal sequencing of pumps depends on the sequencing of chillers.

An additional pump should be brought online whenever the current set of pumps is operating at full capacity and can no longer satisfy the differential pressure set point. This situation can be detected by monitoring the differential pressure or the controller output signal. Insufficient pump capacity leads to extended periods with differential pressures that are less than the set point and a controller output that is saturated at 100%. A pump may be taken offline whenever the remaining pumps have sufficient capacity to maintain the differential pressure set point. This condition can be determined by comparing the current (time-averaged) controller output with the controller output (time-averaged) at the point just after the last pump was brought online. The pump can be brought offline when the current output is less than the switch point value by a specified dead band (e.g., 5%).

Overrides for Equipment and Comfort Constraints

The chilled-water temperature is bounded by upper and lower limits dictated by comfort, humidity, and equipment safety concerns. However, within these bounds, the chilled-water temperature may not always be low enough to maintain supply air set-point temperatures for the cooling coils. This situation might occur at high loads when the chilled-water flow is at a maximum and is detectable by monitoring the coil discharge air temperatures. Limits on the pressure differential set point might also be imposed to ensure adequate controllability of the cooling-coil control valves.

Implementation

Before commissioning, the parameters of the open-loop control for chilled-water set point [Equation (10)] need to be estimated

using the results of Table 4. After the system is in operation, these parameters may be fine-tuned with measurements as outlined in the section on Control Optimization Methods. With the parameters specified, the control algorithm is separated into two reset strategies: chilled-water temperature and pressure differential.

Chilled-Water Temperature Reset. The chilled-water supply temperature set point is reset at fixed decision intervals (e.g., 15 min) using the following procedure:

1. Determine the time-averaged position of (or controller output for) the cooling-coil water valves and corresponding discharge air temperatures for "representative" air handlers over the previous decision interval.
2. If more than one valve is saturated at 100% open and their corresponding discharge air temperatures are greater than set point (e.g., 1°F), then decrease the chilled-water temperature by a fixed amount (e.g., 0.5°F) and go to step 5. Otherwise, go to step 3.
3. Determine the total chilled-water flow and load.
4. Estimate an optimal chilled-water set point with Equations (9) and (10). Increase or decrease the actual set point in the direction of the near-optimal value by a fixed amount (e.g., 1°F).
5. Limit the new set point between upper and lower constraints dictated by comfort and equipment safety.

Pump Sequencing. Secondary pumps should be brought online or offline at fixed decision intervals (e.g., 15 min) with the following logic:

1. Evaluate the time-averaged pump controller output over the previous decision interval.
2. If the pump controller is saturated at 100%, then bring the next pump online. Otherwise, go to step 3.
3. If the pump control output is significantly less (e.g., 5%) than the value associated with the first time interval after the last pump was brought online, then bring that pump offline.

Differential Pressure Reset. The set point for differential pressure between supply and return lines should be reset at smaller time intervals than the supply water temperature reset and pump sequencing strategies (e.g., 5 min) using the following procedure:

1. Check the water valve positions (or controller output) for "representative" air handlers and determine the time-averaged values over the last decision interval.
2. If more than one valve has been saturated at 100% open, then increase the differential pressure set point by a fixed value (e.g., 5% of the design value) and go to step 4. Otherwise, go to step 3.
3. If none of the valves have been saturated, then decrease the differential pressure set point by a fixed value (e.g., 5% of the design value).
4. Limit the differential pressure set point between upper and lower constraints.

SEQUENCING AND LOADING MULTIPLE CHILLERS

Multiple chillers are normally configured in parallel and typically controlled to give identical chilled-water supply temperatures. In most cases, controlling for identical set temperatures is the best and simplest strategy. With this approach, the relative loading on operating chillers is controlled by the relative chilled-water flow rates. Typically, the distribution of flow rates to heat exchangers for both chilled and condenser water are dictated by chiller pressure drop characteristics and may be adjusted through flow balancing, but are not controlled using a feedback controller. In addition to the distribution of chilled and condenser water flow rates, the chiller sequencing affects energy consumption. Chiller sequencing defines the conditions under which chillers are brought online and offline.

Simple guidelines may be established for each of these controls to provide near-optimal operation.

Near-Optimal Condenser Water Flow Distribution

In general, the condenser water flow to each chiller should be set to give identical leaving condenser water temperatures. This condition approximately corresponds to relative condenser flow rates equal to the relative loads on the chillers, even if the chillers are loaded unevenly. Figure 27 shows results for four sets of two chillers operated in parallel. The curves represent data from chillers at three different installations: (1) a 5500 ton variable-speed chiller at the Dallas-Ft. Worth airport, Texas (Braun et al. 1989a); (2) a 550 ton fixed-speed chiller at an office building in Atlanta (Hackner et al. 1984, 1985); and (3) a 1250 ton fixed-speed chiller at a large office building in Charlotte, North Carolina (Lau et al. 1985). The capacities of the chillers in the two office buildings were scaled up for comparison with the Dallas-Ft. Worth airport chiller.

The overall chiller coefficient of performance (COP) is plotted versus the difference between the condenser water return temperatures for equal chiller loading. For multiple chillers having similar performance characteristics (either variable- or fixed-speed), it is best to distribute the condenser water flow rates so that each chiller has the same leaving condenser water temperature. For situations where chillers do not have identical performance, equal leaving condenser water temperatures result in chiller performance that is close to the optimum. Even for variable- and fixed-speed chiller combinations that have very different performance characteristics, the penalty associated with using identical condenser leaving-water temperatures is small. To achieve equal condenser leaving-water temperatures, it is necessary to properly balance the condenser water flow rates at design operating conditions.

Optimal Chiller Load Distribution

Assuming identical chilled-water return and chiller supply temperatures, the relative chilled-water load for each parallel chiller (load divided by total load) that is operating could be controlled by its relative chilled-water flow rate (flow divided by total flow). To change the relative loadings in response to operating conditions, the individual flow rates must be controlled. However, this is typically not done and it is probably sufficient to establish the load distributions based on design information and then balance the flow rates to achieve these load distributions. Alternatively, the individual chiller

loads can be precisely controlled through variation of individual chiller supply water set points.

Chillers with Similar Performance Characteristics. Braun et al. (1989a) showed that, for chillers with identical design COPs and part-load characteristics, a minimum or maximum power consumption occurs when each chiller is loaded according to the ratio of its capacity to the total capacity of all operating chillers. This is equivalent to each chiller operating at equal part-load ratios (load divided by cooling capacity at design conditions). For the ith chiller, the optimal chiller loading is then

$$\dot{Q}_{ch,i}^{*} = \frac{\dot{Q}_{load}}{\sum_{i=1}^{N} \dot{Q}_{ch,des,i}} \dot{Q}_{ch,des,i} \tag{13}$$

where $\dot{Q}_{load}$ is the total chiller load, $\dot{Q}_{ch,des,i}$ is the cooling capacity of the ith chiller at design conditions, and N is the number of chillers operating.

The loading determined with Equation (13) could result in either minimum or maximum power consumption. However, this solution gives a minimum when the chillers are operating at loads greater than the point at which the maximum COP occurs (i.e., chiller COP decreases with increased loading). Typically, the maximum COP occurs at loads that are less than the nominal design capacity.

Figure 28 shows the effect of relative loading on chiller COP for different sets of identical chillers loaded at approximately 70% of their total capacities. Three of the chiller sets have maximum COPs when evenly loaded [matching the criterion of Equation (13)], whereas the fourth (Dallas-Ft. Worth fixed-speed) obtains a minimum at that point. The part-load characteristic of the Dallas-Ft. Worth fixed-speed chiller is unusual in that the maximum overall COP occurs at its maximum capacity. This chiller was retrofitted with a different refrigerant and drive motor, which derated its capacity from 8700 to 5500 tons. As a result, the evaporators and condensers are oversized for its current capacity. Overall, the penalty associated with equally loading the Dallas-Ft. Worth fixed-speed chillers is small compared with optimal loading, and this strategy is probably appropriate. However, a slight reduction in energy consumption is possible if one of the two chillers operates at full capacity. The loading criterion of Equation (13) also
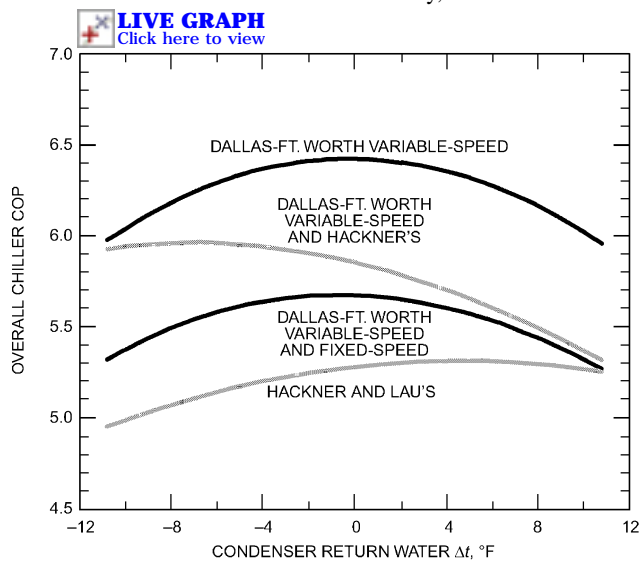
Fig. 27 Effect of Condenser Water Flow Distribution for Two Chillers In Parallel
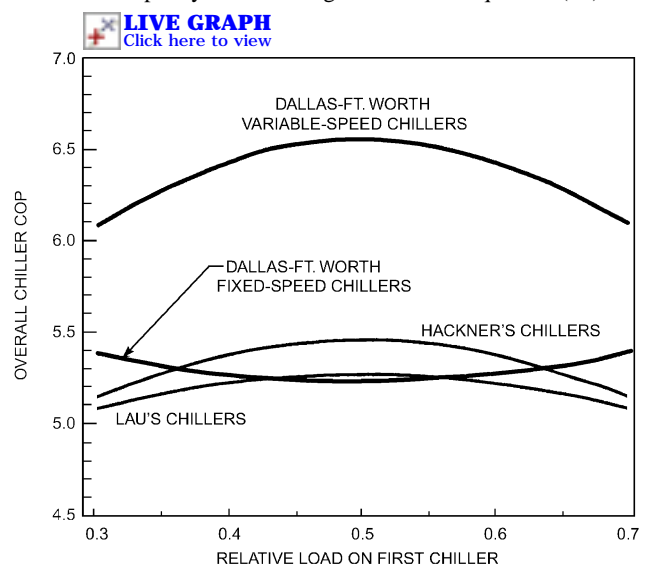
Fig. 28 Effect of Relative Loading for Two Identical Parallel Chillers

works well for many combinations of chillers with different performance characteristics.

To achieve specified relative chiller loadings with equal chilled-water set points, chilled-water flow rates must be properly balanced. The relative loadings of Equation (13) only depend on design information, and flow balancing can be achieved through proper design and commissioning.

Chillers with Different Performance Characteristics. For the general case of chillers with significantly different part-load characteristics, a point of minimum or maximum overall power occurs where the partial derivatives of the individual chiller's power consumption with respect to their loads are equal:

$$\frac{\partial P_{ch,i}}{\partial \dot{Q}_{ch,i}} = \frac{\partial P_{ch,j}}{\partial \dot{Q}_{ch,j}} \qquad \text{for all } i \text{ and } j \tag{14}$$

and subject to the constraint that

$$\sum_{i=1}^{N} \dot{Q}_{ch,i} = \dot{Q}_{load} \tag{15}$$

where $\dot{Q}_{ch,i}$ is the cooling load for the ith chiller and $\dot{Q}_{load}$ is the total cooling load.

In general, the power consumption of a chiller can be correlated as a quadratic function of cooling load and difference between the leaving condenser water and chilled-water supply temperatures according to

$$P_{ch,i} = a_{0,i} + a_{1,i}(t_{cwr,i} - t_{chws,i}) + a_{2,i}(t_{cwr,i} - t_{chws,i})^2 \\ + a_{3,i}\dot{Q}_{ch,i} + a_{4,i}\dot{Q}_{ch,i}^2 + a_{5,i}(t_{cwr,i} - t_{chws,i})\dot{Q}_{ch,i} \tag{16}$$

where, for the ith chiller, t_{cwr} is the leaving condenser water temperature and t_{chws} is the chilled-water supply temperature. The coefficients of Equation (16) ($a_{0,i}$ to $a_{5,i}$) can be determined for each chiller through regression applied to measured or manufacturers' data.

If each chiller has identical leaving condenser and chilled-water supply temperatures, the criterion of Equation (14) applied to the correlation of Equation (16) leads to

$$a_{3,i} + 2a_{4,i}\dot{Q}_{ch,i}^* + a_{5,i}(t_{cwr} - t_{chws}) \\ = a_{3,j} + 2a_{4,j}\dot{Q}_{ch,j}^* + a_{5,j}(t_{cwr} - t_{chws}) \qquad \text{for } i \neq j \tag{17}$$

where $\dot{Q}_{ch,i}^*$ is the optimal load for the ith chiller.

Equations (17) and (15) represent a system of N linear equations in terms of N chiller loads that can be solved to give minimum (or possibly maximum) power consumption. For a given combination of chillers, the solution depends on the operating temperatures and total load. However, the individual chiller loads must be constrained to be less than the maximum chiller capacity at these conditions. If an individual chiller load determined from these equations is greater than its cooling capacity, then this chiller should be fully loaded and Equations (17) and (15) should be resolved for the remaining chillers [Equation (17) should only include unconstrained chillers].

To control individual chiller loads with identical chilled-water supply temperatures, individual chilled-water flow rates need to be controlled with two-way valves, which is not typical. However, the distribution of chiller loads could be changed for a fixed-flow distribution by using different chilled-water set-point temperatures. For a given flow and load distribution, the individual chiller set point for parallel chillers is determined according to

$$t_{chws,i} = t_{chwr} - \frac{\dot{Q}_{ch,i}}{f_{F,i}\dot{Q}_{load}}(t_{chwr} - t_{chws}^*) \tag{18}$$

where $f_{F,i}$ is the flow for the ith chiller divided by total flow, t_{chws}^* is the chilled-water supply temperature set point for the combination of chillers determined using the previously defined reset strategies, and t_{chwr} is the temperature of water returned to chillers from the building.

Substituting Equation (18) into Equation (16) and then applying the criterion of Equation (14) leads to the following:

$$A_i + B_i\dot{Q}_{ch,i}^* = A_j + B_j\dot{Q}_{ch,j}^* \qquad \text{for } i \neq j \tag{19}$$

where

$$A_i = a_{3,i} + [a_{1,i} + 2a_{2,i}(t_{cwr} - t_{chwr})]\frac{t_{chwr} - t_{chws}^*}{f_{F,i}\dot{Q}_{load}} \\ + a_{5,i}(t_{cwr} - t_{chws}^*)$$

$$B_i = 2\left[a_{4,i} + a_{5,i}\frac{t_{chwr} - t_{chws}^*}{f_{F,i}\dot{Q}_{load}} + a_{2,i}\left(\frac{t_{chwr} - t_{chws}^*}{f_{F,i}\dot{Q}_{load}}\right)^2\right]$$

Optimal chiller loads are determined by solving the linear system of equations represented by Equations (19) and (15). The individual chiller set points are then evaluated with Equation (18). If any set points are less than the minimum set point or greater than the maximum set point, then the set point should be constrained and Equations (19) and (15) should be resolved for the remaining chillers [Equation (19) should only include unconstrained chillers].

Example 3. Determine the optimal loading for two chillers using the three methods outlined in this section. Table 6 gives the design cooling capacities and coefficients of the curve-fit of Equation (16) for the two chillers. The chillers are operating with a total cooling load of 1440 tons, condenser water return temperature of 85°F, an overall chilled-water supply temperature set point of 45°F, and a chilled-water return temperature of 55°F. Figure 29 shows the COPs for the two chillers as a function load relative to their design loads for the given operating temperatures. Chiller 1 is more efficient at higher part-ratios and less efficient at lower part-load ratios as compared with chiller 2.

Solution:

First, consider operating the chillers at equal part-load ratios. The ratio of the cooling load to the cooling capacity of the operating chillers is 1440/(1250 + 550) = 0.85. From Equation (13), the individual chiller loads are

$$\dot{Q}_{ch,1}^* = 0.8(1250 \text{ tons}) = 1000 \text{ tons}$$

$$\dot{Q}_{ch,2}^* = 0.8(550 \text{ tons}) = 440 \text{ tons}$$
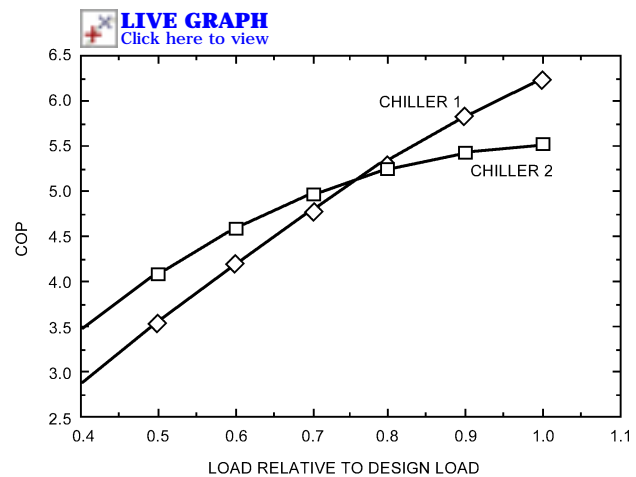
Fig. 29   Chiller COP for Two Chillers

**Table 5 Chiller Characteristics for
Optimal Loading Example 3**

Variable	Units	Chiller 1	Chiller 2
$\dot{Q}_{ch,des,i}$	tons	1250	550
$a_{0,i}$	kW	106.4	119.7
$a_{1,i}$	kW/°F	6.147	0.1875
$a_{2,i}$	kW/°F^2	0.1792	0.04789
$a_{3,i}$	kW/ton	−0.0735	−0.3673
$a_{4,i}$	kW/ton^2	0.0001324	0.0005324
$a_{5,i}$	kW/ton·°F	−0.001009	0.008526

The power for each chiller is computed for the specified operating conditions with Equation (16) and the coefficients of Table 5. For the case of equal part-load ratios, the total chiller power consumption is

$$P_{ch} = P_{ch,1} + P_{ch,2} = 657.5 \text{ kW} + 295.3 \text{ kW} = 952.8 \text{ kW}$$

A second solution is determined for optimal chiller loads for the case of equal chilled-water temperature set points and controllable flow for each chiller. In this case, algebraic manipulation of Equations (15) and (17) produces the following results for the individual chiller loads:

$$\dot{Q}^*_{ch,1} = \frac{(a_{3,2} - a_{3,1}) + 2a_{4,2}\dot{Q}_{load} + (a_{5,2} - a_{5,1})(t_{cwr} - t_{chws})}{2(a_{4,1} + a_{4,2})}$$

$$= 1219 \text{ tons}$$

$$\dot{Q}_{ch,2} = \dot{Q}_{load} - \dot{Q}_{ch,1} = 221 \text{ tons}$$

The resulting power consumption is then

$$P_{ch} = P_{ch,1} + P_{ch,2} = 696.9 \text{ kW} + 224 \text{ kW} = 920.9 \text{ kW}$$

Optimal loading of the chillers reduces the overall chiller power consumption by about 4% through heavier loading of chiller 1 and lighter loading of chiller 2 (see Figure 29).

Finally, optimal chiller loading is determined for the case where individual loadings are controlled by using different chilled-water temperature set points (individual flow is not controllable). To apply Equations (18) and (19), the relative chilled-water flow rate for each chiller must be known. For this example, the relative flow for the ith chiller is assumed to be equal to the ratio of its design capacity to the design capacity for the operating chillers, so that

$$f_{F,1} = \frac{\dot{Q}_{ch,des,1}}{\dot{Q}_{ch,des,1} + \dot{Q}_{ch,des,2}} = \frac{1250}{1250 + 550} = 0.694$$

$$f_{F,2} = \frac{\dot{Q}_{ch,des,2}}{\dot{Q}_{ch,des,1} + \dot{Q}_{ch,des,2}} = \frac{550}{1250 + 550} = 0.306$$

Then, solving Equations (15) and (19) leads to the following results for the individual chiller loads:

$$\dot{Q}^*_{ch,1} = \frac{(A_2 - A_1) + B_2\dot{Q}_{load}}{B_1 + B_2} = 1153 \text{ tons}$$

$$\dot{Q}_{ch,2} = \dot{Q}_{load} - \dot{Q}_{ch,1} = 287 \text{ tons}$$

These loads lead to a total chiller power consumption of

$$P_{ch} = P_{ch,1} + P_{ch,2} = 713.8 \text{ kW} + 218.1 \text{ kW} = 931.9 \text{ kW}$$

Individual chilled-water set points are determined from Equation (18) and are 43.5 and 48.5°F for chillers 1 and 2, respectively. Power consumption has increased slightly from the case of identical chiller set points and variable flow.

Note that changing either flows or chilled-water set points complicates overall system control as compared with loading the chillers with fixed part-load ratios, and leads to relatively small savings.

Order for Bringing Chillers Online and Offline

For chillers with similar efficiencies, the order in which chillers are brought online and offline may be dictated by their cooling capacities and the desire to provide even runtimes. However, whenever beneficial and possible, chillers should be brought online in an order that minimizes the incremental increase in energy consumption. At a given condition, the power consumption of any chiller can be evaluated using the correlation given by Equation (16), where the coefficients are determined using manufacturers' data or in-situ measurements. Then, the overall power consumption for all operating chillers is

$$P_{ch} = \sum_{i=1}^{N} P_{ch,i} \qquad (20)$$

When additional chiller capacity is required (see next section), the projected power of all valid chiller combinations should be evaluated using Equation (16), with the projected load determined by Equation (13) for chillers with similar performance characteristics, or the solution of Equations (14) subject to the constraint in Equation (15) for chillers with significantly different performance characteristics. Valid chiller combinations involve chillers that are not in alarm or locked out, and with load ratios between a low limit (e.g., 30%) and 100%. The best chiller combination to bring on line should result in the smallest increase (or largest decrease) in overall chiller power consumption as estimated with Equations (20) and (16) with chiller loading determined as outlined in the previous section. For systems with dedicated chilled-water and condenser water pumps and/or cooling towers, the associated power of this equipment should be added to Equation (16) to estimate the load of the chiller plus its auxiliary equipment. It is recommended that these estimates be performed online using in-situ measurements of each chiller's discharge chilled-water temperature and entering condenser water temperature, and the projected load of the chiller. A chiller should be shut down when its load drops below the spare capacity load of the current number of online chillers; for a primary/secondary chilled-water system, the primary chilled-water flow will remain above the secondary chilled-water flow once the chiller is shut down. (The spare capacity load is equal to the rated capacity of the online chillers minus the actual measured load of the online chillers.)

For chillers with similar design cooling capacities, a simpler (although suboptimal) approach can be used for determining the order for bringing chillers online and offline. In this case, the chiller with the highest peak COP can be brought online first, followed by the second most efficient chiller, etc., and then brought offline in reverse order. The maximum COP for each chiller can be evaluated using manufacturers' design and part-load data or from curve-fits to in-situ performance.

The chiller load associated with maximum COP for each chiller can be determined by applying a first-order condition for a maximum, using Equation (16) and the definition of COP. For this functional form, the maximum (or possibly minimum) COP occurs for

$$\dot{Q}^*_{ch,i} = \sqrt{\frac{a_{0,i} + a_{1,i}(t_{cwr} - t_{chws}) + a_{2,i}(t_{cwr} - t_{chws})^2}{a_{4,i}}} \qquad (21)$$

The load determined from Equation (21) yields a maximum COP whenever it is real and bounded between upper and lower limits. Otherwise, it can be assumed that the maximum COP occurs at full load conditions. Typically, the maximum COP occurs between about 40 and 80% of design load and increases as the temperature difference between the condenser leaving water and chilled-water
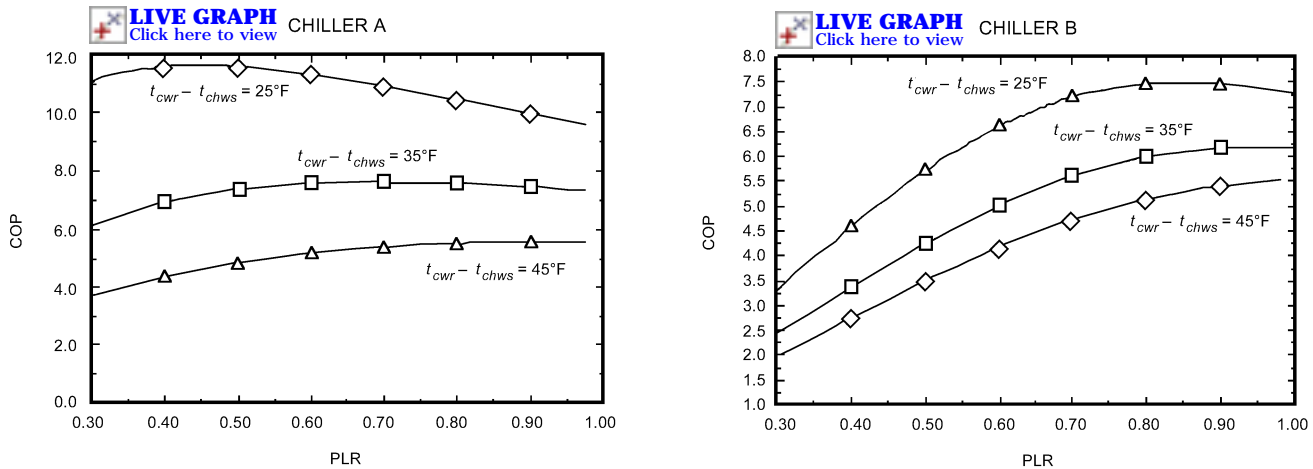
Fig. 30   **Chiller A and B Performance Characteristics for Maximum COP, Example 4**

Table 6   **Chiller Characteristics for Maximum COP, Example 4**

Variable	Unit	Chiller A	Chiller B
$\dot{Q}_{ch,des,i}$	tons	5421	5421
$a_{0,i}$	kW	262.6	187.2
$a_{1,i}$	kW/°F	–25.36	96.19
$a_{2,i}$	kW/°F^2	0.9718	–0.4314
$a_{3,i}$	kW/ton	–0.02568	–0.4314
$a_{4,i}$	kW/ton^2	0.00004046	0.0001106
$a_{5,i}$	kW/ton·°F	0.005289	–0.004537

Table 7   **Results for Maximum COP, Example 4**

Variable	Chiller A	Chiller B
$\dot{Q}^*_{ch,i}$	3738 ton	5229 ton
PLR$_i$	0.690	0.965
$P_{ch,i}$	1727 kW	2964 kW
COP$_i$	7.61	6.21

supply decreases. Equation (21) could be applied online to determine the rank ordering of chillers to bring online as a function of operating temperatures. However, it is often sufficient to use Equation (21) at the design temperature difference and establish a chiller sequencing order at the design or commissioning stage.

Example 4. Determine the loads for maximum COP for two different chillers at a chilled-water set point of 45°F and a condenser water return temperature of 80°F. Table 6 gives the design cooling capacities and coefficients of the curve-fit of Equation (16) for the two chillers. Figure 30 shows the COPs of the two chillers determined from the correlations as a function of relative load (PLR) and temperature difference ($t_{cwr} - t_{chws}$). These chillers have identical performance at design conditions, but very different part-load characteristics because of different methods used for capacity control.

Solution:

Loading associated with the maximum COP for each chiller is determined using Equation (21) and the coefficients of Table 7. Power for each chiller is then determined using Equation (16) and the COP follows directly. Results of the calculations are given in Table 7. The maximum COP for chiller A is about 20% greater than that for chiller B at the specified operating temperatures and should be brought online first.

Load Conditions for Bringing Chillers Online or Offline

In general, chillers should be brought online at conditions where the total power (including pumps and tower or condenser fans) of operating with the additional chiller would be less than without it. Conversely, a chiller should be taken offline when the total power of operating with that chiller would be less than with it. In practice, the switch point for bringing a chiller online should be greater than that for bringing that same chiller offline (e.g., 10%), to ensure stable control. The optimal sequencing of chillers depends primarily on their part-load characteristics and the manner in which the chiller pumps are controlled.

Dedicated Pumps. Where individual condenser and chilled-water pumps are dedicated to the chiller, Braun et al. (1989a) and Hackner et al. (1985) showed that a chiller should be brought online when the operating chillers reach their capacity. This conclusion is the result of considering both the chiller and pumping power in determining optimal control. If pumping power is ignored, the optimal chiller sequencing occurs when chiller efficiency is maximized at each load. Because maximum efficiency often occurs at part-load conditions, the optimal point for adding or removing chillers may occur when chillers are operating at less than their capacity. However, the additional pumping power required for bringing additional pumps online with the chiller offsets any reductions in overall chiller power consumption associated with part-load operation.

When pumps are dedicated to chillers, situations may arise where chillers are operating at less than their capacity but chilled-water flow to the cooling coils is insufficient to meet the building load. This generally results from inadequate design or improper maintenance. Under these circumstances, either some zone conditions need to float to reduce the chilled-water set point (if possible), or an additional chiller needs to be brought online. Monitoring zone air-handler conditions is one way to detect this situation. If (1) the chilled-water set point is at its lower limit, (2) any air-handler water control valves are saturated at 100% open, and (3) their corresponding discharge air temperatures are significantly greater (e.g., 2°F) than set point, then the chilled-water flow is probably insufficient and an additional chiller/pump combination could be brought online. One advantage of this approach is that it is consistent with the reset strategies for both fixed- and variable-speed chilled-water systems.

Chillers can be brought online or offline with the following logic:

1. Evaluate the time-averaged values of the chilled-water supply temperature and overall cooling load over a fixed time interval (e.g., 5 min).
2. If the chilled-water supply temperature is significantly greater than the set point (e.g., 1°F), then bring the next chiller online. Otherwise, go to step 3.
3. Determine the time-averaged position of the cooling-coil water valves and corresponding discharge air temperatures for "representative" air handlers.

4. If the chilled-water supply set point is at its lower limit, more than one valve is saturated at 100% open, and their corresponding discharge air temperatures are significantly greater than set point (e.g., 1°F), then bring another chiller/pump combination online. Otherwise, go to step 5.

5. If the cooling load is significantly less (e.g., 10%) than the value associated with the first time interval after the last chiller was brought online, then take that chiller offline.

Nondedicated Pumps. For systems without dedicated chiller pumps (e.g., variable-speed primary systems), the optimal load conditions for bringing chillers online or offline do not generally occur at full chiller capacity. In determining optimal chiller switch points, ideally both chiller and pumping power should be considered because pressure drop characteristics and pumping change when a chiller is brought online or offline. However, simple estimates of optimal switch points may be determined by considering only chiller power.

A chiller should be brought online whenever it would reduce the overall chiller power or if the current chillers can no longer meet the load (see previous section). A chiller should be added if the power consumption associated with $(N + 1)$ chillers is significantly less (e.g., 5%) than the current N chillers, with both conditions evaluated using Equation (20) with correlations of the form given in Equation (16), and sequencing and loading determined as outlined in previous sections. Conversely, a chiller should be removed if the power consumption associated with the $(N - 1)$ chillers is significantly less (e.g., 5%) than the current N chillers. The decision to add or remove chillers is readily determined using the current load and operating temperatures.

STRATEGIES FOR BOILERS

Load Conditions for Bringing Boilers Online or Offline

The specifics of the strategy for bringing boilers online depend on the type of boiler. Hot-water boilers have dedicated or nondedicated hot-water pumps; steam boilers do not have hot-water pumps, but rely on differences in steam pressure between the boiler steam header discharge and the point of use to distribute steam throughout the system.

Hot-Water Boilers with Dedicated Pumps. The strategy for hot-water boilers with dedicated hot-water pumps is similar to that for chillers with dedicated chilled-water and condenser water pumps: another boiler should be brought online when operating boilers reach capacity, because the efficiency of the boiler should include the power to drive its associated hot-water pump. This can be determined when hot-water temperature drops below its set point for a predetermined time interval (e.g., 5 min).

Hot-water boilers with dedicated pumps can be brought online and offline with the following logic:

1. Continuously calculate the load ratio of each boiler or boiler combination. For the ith boiler,

$$\text{LR}_i = \frac{\dot{Q}_{load}}{\dot{Q}_{blr,des,i}} \tag{22}$$

where LR_i is load ratio of the ith boiler combination, $\dot{Q}_{load}$ is the total boiler plant load, and $\dot{Q}_{blr,des,i}$ is the design (rated) output of the ith boiler combination.

2. Every sampling interval (e.g., 60 s), calculate the predicted input fuel requirement for each boiler combination as

$$\text{IF}_i = \frac{(\text{LR}_i)\dot{Q}_{blr,des,i}}{\eta_i} \tag{23}$$

where IF_i is the input fuel requirement and η_i is the efficiency of the ith boiler combination.

3. Continuously evaluate time-averaged values of the hot-water supply temperature over a fixed time interval (e.g., 5 min).

4. If the hot-water supply temperature drops below its set point for a predetermined time interval (e.g., 5 min), then, from boiler part-load performance curves, select the boiler combination with a load ratio between 0.5 and 1.0 and with the least input fuel requirement to meet the load, and turn this combination of boilers on. Note that this strategy greatly reduces the possibility of short-cycling boilers because the new combination of boilers to be started likely includes boilers already operating (i.e., only one additional boiler is likely to be added).

5. If the capacity of the least efficient online boiler drops below the spare capacity of the current number of boilers operating (or for a primary/secondary hot-water system, if the flow rate of the associated primary hot-water pump is less than the difference between primary and secondary hot-water flow rates) for a predetermined time interval (e.g., 5 min), then shut down and bank this boiler in hot standby.

Hot-Water Boilers with Nondedicated Pumps or Steam Boilers. For hot-water systems without dedicated hot-water pumps or for steam systems, the optimal load conditions for bringing boilers online or offline do not generally occur at the full capacity of the online boilers. For these systems, a new boiler combination should be brought online whenever the hot-water supply temperature or steam pressure falls below set point for a predetermined time interval (e.g., 5 min) *and* the part-load efficiency curves of the boiler combination predicts that the new combination of boilers can meet the required load using significantly less (e.g., 5%) input fuel.

Optimal Boiler Load Distribution

Optimal load distribution strategies for boilers are similar to those for chillers. For boilers with similar performance characteristics, the optimal boiler loading is similar to Equation (13) for chillers:

$$\dot{Q}_{blr,i}^* = \frac{\dot{Q}_{load}}{\sum_{i=1}^{N} \dot{Q}_{blr,des,i}} \dot{Q}_{blr,des,i} \tag{24}$$

where $\dot{Q}_{blr,i}^*$ is the optimal load for the ith boiler.

For boilers with significantly different performance characteristics, the criterion for optimal boiler loading is similar to Equations (14) and (15) for chillers, except that boiler cost of operation is used:

$$\frac{\partial C_{blr,i}}{\partial \dot{Q}_{blr,i}} = \frac{\partial C_{blr,j}}{\partial \dot{Q}_{blr,j}} \qquad \text{for all } i \text{ and } j \tag{25}$$

and subject to the constraint that

$$\sum_{i=1}^{N} \dot{Q}_{blr,i} = \dot{Q}_{load} \tag{26}$$

where $C_{blr,i}$ and $C_{blr,j}$ are the operating costs of boiler i and j, respectively, $\dot{Q}_{blr,i}$ is the heating load for the ith boiler, and $\dot{Q}_{load}$ is the total heating load.

In general, the boiler operating-cost curve can be calculated as a quadratic function of heating load only. For the ith boiler,

$$C_{blr,i} = b_{0,i}\dot{Q}_{blr,i}^2 + b_{1,i}\dot{Q}_{blr,i} + b_{2,i} \tag{27}$$

Applying the criterion of Equation (25) to Equation (27),

$$2b_{0,i}\dot{Q}_{blr,i}^* + b_{1,i} = 2b_{0,j}\dot{Q}_{blr,j}^* + b_{1,j} \tag{28}$$

where $\dot{Q}_{blr,i}^*$ is the optimal load for the ith boiler.

Maintaining Boilers in Standby Mode

It is generally more economical to run fewer boilers at a high rating. However, the integrity of the steam or hot-water supply must be maintained in the event of a forced outage of one of the operating boilers or if the facility experiences highly diverse load swings throughout the heating season. Both conditions can often be satisfied by maintaining a boiler in standby or "live bank" mode. For example, in this mode, a steam boiler is isolated from the steam system at no load but is kept at system operating pressure by periodic firing of either the igniters or a main burner to counteract ambient heat losses.

Supply Water and Supply Pressure Reset for Boilers

Simple control strategies can be used to generate a suboptimal hot-water temperature (for hot-water boilers) or steam pressure (for steam boilers). An energy management and control system must be interfaced to the boiler controls and be capable of monitoring the position of the valve controlling the flow of hot water to the heating coils or steam pressure at the most critical zone. For a hot-water system,

1. Continuously monitor the hot-water valve position of the various heating zones.
2. If none of the hot-water valves are greater than 95% open, lower boiler hot-water supply temperature by a small increment (e.g., 1°F) each reset time interval (a predetermined interval established by system thermal lag characteristics, e.g., 15 to 20 min).
3. Once one hot-water valve opens beyond 95%, stop downward resets of boiler hot-water temperature set point.
4. If two or more hot-water valves open beyond 95%, raise boiler hot-water temperature set point by a small increment (e.g., 1°F) each reset interval.

For a steam system, the steam header pressure should be lowered to a value that just satisfies the highest pressure demand. *Caution*: for nongravity condensate return systems, steam pressure reset could impede condensate return (see Chapter 10 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*).

STRATEGIES FOR AIR-HANDLING UNITS

Air Handler Sequencing and Economizer Cooling

Traditional air handler sequencing strategies use a single PI controller to control heating, cooling with outside air, mechanical cooling with 100% outside air, and mechanical cooling with minimum outside air. Sequencing between these different modes is accomplished by splitting the controller output into different regions of operation, as shown in Figure 31.
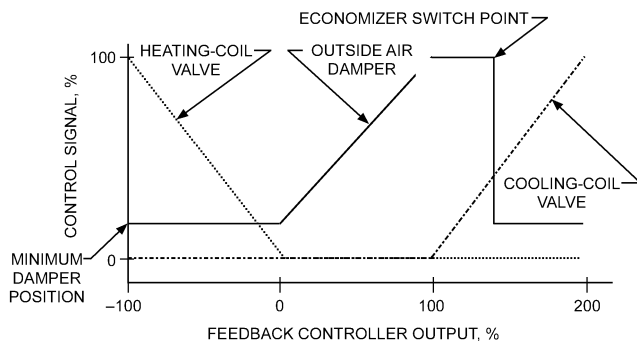
Fig. 31   AHU Sequencing Strategy with Single Feedback Controller

Figure 31 depicts the relationship between the control signal to the valves and dampers and the feedback controller output. The controller adjusts its output to maintain the supply air temperature set point. If its output is between 100 and 200%, mechanical cooling is used. When outside conditions are suitable, the outside air dampers switch from minimum position (minimum ventilation air) to fully open. For a dry-bulb economizer, this switch point occurs when ambient air is less than a specified value. This switch point should be less than the switch point to return to minimum outside air, to ensure stable control. The economizer switchover temperature may be significantly lower than the return air temperature (e.g., 10°F lower) in humid climates where latent ventilation loads are significant. However, in dry climates, the switchover temperature may be close to the return temperature (e.g., 75°F). An enthalpy (or wet-bulb) economizer compares the outside and return air enthalpies (or wet-bulb temperatures) to initiate or terminate economizer operation. In general, enthalpy economizers yield lower energy costs than dry-bulb economizers, but require measurements of the outside and return air humidity. Humidity sensors require regular maintenance to ensure accurate readings. When controller output is between 0 and 100% (see Figure 31), the cooling coil valve is fully closed and cooling is provided by ambient air only. In this case, the controller output modulates the position of the outside air dampers to maintain the set point. If the controller output signal is between –100 and 0%, the heating coil is used to maintain set point and the outside air dampers are set at their minimum position.

A single feedback controller is difficult to tune to perform well for all four modes of operation associated with an AHU. An alternative to the traditional sequencing strategy is to use three separate feedback controllers, as described by Seem et al. (1999). This approach can improve temperature control, reduce actuator usage, and reduce energy costs. Figure 32 shows a state transition diagram for implementing a sequencing strategy that incorporates separate feedback controllers.

In state 1, a feedback controller adjusts the heating valve to maintain the supply air set-point temperature with minimum outside air. The transition to state 2 occurs after the control signal has been saturated at the no-heating position for a period equal to a specified state transition delay (e.g., 3 min). In state 2, a second feedback controller adjusts the outside and return air dampers to achieve set point with heating and cooling valves closed. Transition back to state 1
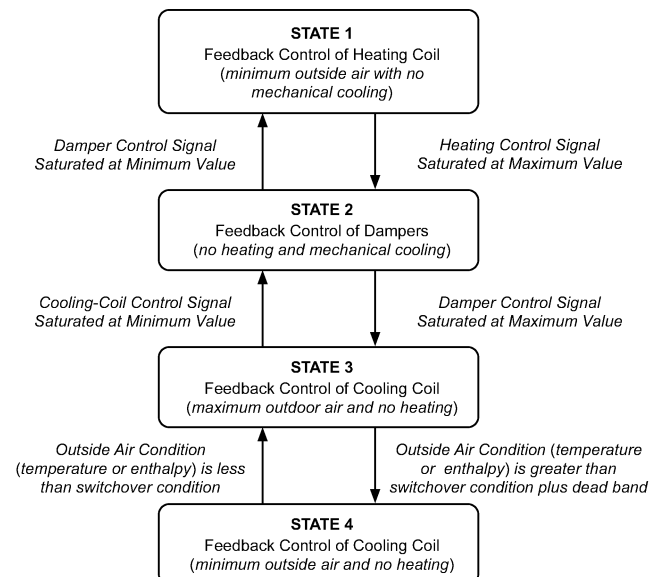
Fig. 32   AHU Sequencing Strategy with Multiple Feedback Controllers

only occurs after the damper control signal is saturated at its minimum value for the state transition delay, whereas transition to state 3 is associated with saturation at the maximum damper position for the state transition delay. In state 3, the outside air damper remains fully open and a third feedback controller is used to adjust the flow of cooling water to maintain the supply air temperature at set point. Transition back to state 2 occurs if the controller output is saturated at its minimum value for the state transition delay. For a dry-bulb economizer, transition to state 4 occurs when the ambient dry-bulb temperature is greater than the switchover temperature by a dead band (e.g., 2°F). The feedback controller continues to modulate the cooling-coil valve to achieve set point. Transition back to state 3 occurs when the ambient dry-bulb is less than the switchover temperature (e.g., 65°F). For an enthalpy economizer, the ambient enthalpy is compared with return air enthalpy to initiate transitions between states 3 and 4.

Supply Air Temperature Reset for Constant Air Volume (CAV)

The benefits of resetting supply air temperature set points for CAV systems are significant. Increasing the supply air set point for cooling reduces both the cooling and reheat required, but does not change fan energy. In general, the set point for a CAV system could be set at the highest value that will keep all zone temperatures at their set points and all humidities within acceptable limits. A simple reset strategy based on this concept follows.

At each the decision interval (e.g., 5 min), the following logic can be applied:

1. Check controller outputs for representative zone reheat units and determine time-averaged values over the last decision interval.
2. If any controller output is less than a threshold value (e.g., 5%), then decrease the supply air set point by a fixed value (e.g., 0.5°F) and go to step 4. Otherwise, go to step 3.
3. If all zone humidities are acceptable and all controller outputs are greater than a threshold value (e.g., 10%), then increase the discharge air set point by a fixed value (e.g., 0.5°F) and go to step 4. Otherwise, do not change the set point.
4. Limit the set point between upper and lower limits based on comfort considerations.

Static Pressure Reset for Variable Air Volume (VAV)

Flow may be modulated in a VAV system by using dampers on the outlet side of the fan, inlet vanes on the fan, vane-axial fans with controllable pitch fan blades, or variable-speed control of the fan motor. Typically, inputs to any of these controlled devices are modulated to maintain a duct static pressure set point as described in Chapter 46. In a single-duct VAV system, the duct static pressure set point is typically selected by the designer to be a fixed value. The sensor is located at a point in the ductwork such that the established set point will ensure proper operation of the zone VAV boxes under varying load (supply airflow) conditions. A shortcoming of this approach is that static pressure is controlled based on a single sensor intended to represent the pressure available to all VAV boxes. Poor location or malfunction of this sensor will cause operating problems.

For a fixed static pressure set point, all of the VAV boxes tend to close as zone loads and flow requirements decrease. Therefore, flow resistance increases with decreasing load. Significant fan energy savings are possible if the static pressure set point is reset so that at least one of the VAV boxes remains open. With this approach, flow resistance remains relatively constant. Englander and Norford (1992), Hartman (1993), Warren and Norford (1993), and Wei et al. (2004) proposed several different strategies based on this concept. Englander and Norford used simulations to show that either static pressure or fan speed can be controlled directly using a flow error

signal from one or more zones and simple rules. Their technique forms the basis of the following reset strategy.

At each decision interval (e.g., 5 min), the following logic can be applied:

1. Check the controller outputs for representative VAV boxes and determine time-averaged values over the last decision interval.
2. If any of the controller outputs are greater than a threshold value (e.g., 98%), then increase the static pressure set point by a fixed value (e.g., 5% of the design range) and go to step 4. Otherwise, go to step 3.
3. If all controller outputs are less than a threshold value (e.g., 90%), then decrease the static pressure set point by a fixed value (e.g., 5% of the design range) and go to step 4. Otherwise, do not change the set point.
4. Limit the set point between upper and lower limits based on upper and lower flow limits and duct design.

STRATEGIES FOR BUILDING ZONE TEMPERATURE SET POINTS

Recovery from Night Setback or Setup

For buildings that are not continuously occupied, significant savings in operating costs may be realized by raising the building set-point temperature for cooling (setup) and by lowering the set point for heating (setback) during unoccupied times. Bloomfield and Fisk (1977) showed energy savings of 12% for a heavyweight building and 34% for a lightweight building.

An optimal controller for return from night setback or setup returns zone temperatures to the comfort range precisely when the building becomes occupied. Seem et al. (1989) compared seven different algorithms for minimum return time. Each method requires estimating parameters from measurements of the actual return times from night setback or setup.

Seem et al. (1989) showed that the optimal return time for cooling was not strongly influenced by the outdoor temperature. The following quadratic function of the initial zone temperature was found to be adequate for estimating the return time:

$$\tau = a_0 + a_1 t_{z,i} + a_2 t_{z,i}^2 \qquad (29)$$

where τ is an estimate of optimal return time, $t_{z,i}$ is initial zone temperature at the beginning of the return period, and a_0, a_1, and a_2 are empirical parameters. The parameters of Equation (29) may be estimated by applying linear least-squares techniques to the difference between the actual return time and the estimates. These parameters may be continuously corrected using recursive updating schemes as outlined by Ljung and Söderström (1983).

For heating, Seem et al. found that ambient temperature has a significant effect on the return time and that the following relationship works well in correlating return times:

$$\tau = a_0 + (1 - w)(a_1 t_{z,i} + a_2 t_{z,i}^2) + w a_3 t_a \qquad (30)$$

where t_a is the ambient temperature, a_0, a_1, a_2, and a_3 are empirical parameters, and w is a weighting function given by

$$w = 1000^{-(t_{z,i} - t_{unocc})/(t_{occ} - t_{unocc})} \qquad (31)$$

where t_{unocc} and t_{occ} are the zone set points for unoccupied and occupied periods. Within the context of Equation (30), this function weights the outdoor temperature more heavily when the initial zone temperature is close to the set-point temperature during the unoccupied time. Again, the parameters of Equation (30) may be estimated by applying linear least-squares techniques to the difference between the actual return time and the estimates.

Ideally, separate equations should be used for zones that have significantly different return times. Equipment operation is initiated for the zone with the earliest return time. In a building with a central cooling system, the equipment should be operated above some minimum load limit. With this constraint, some zones need to be returned to their set points earlier than the optimum time.

Optimal start algorithms often use a measure of the building mass temperature rather than the space temperature to determine return time. Although use of space temperature results in lower energy costs (i.e., shorter return time), the mass temperature may result in better comfort conditions at the time of occupancy.

Emergency Strategy to Limit Peak Cooling Requirements

Keeney and Braun (1997) developed a simple control strategy that uses building thermal mass to reduce peak cooling requirements in the event of a loss of a chiller. This emergency strategy is used only on days where cooling capacity is not sufficient to keep the building in the comfort range using night setup control. It involves precooling the building during unoccupied times and allowing the temperature to float through the comfort zone during occupancy.

The precooling control strategy is depicted in Figure 33 along with conventional night setup control. Precooling is controlled at a constant temperature set point t_{pre}. The warm-up period is used to reset the zone air temperature set point so that the cooling system turns off without calling for heating. During this time, the zone air is warmed by lighting and equipment loads. The occupied set point t_{occ} is set at the low end of the comfort region so that the building mass charge is held as long as cooling capacity is available. This set point is maintained until the limit on cooling capacity is reached. After this point, temperatures in the zones float up and the building thermal mass provides additional cooling. If the precooling and occupied set points have been chosen properly and the cooling capacity is sufficient, zone conditions will remain comfortable throughout the occupied period. The peak cooling requirement can be reduced by as much as 25% using this strategy as compared with night setup control. Thus, the loss of one of four identical chillers could be tolerated. This strategy could also be used for spaces such as auditoriums that have a high occupancy density for a short period.

The length of time and temperature for precooling and the occupied temperature set point chosen for this strategy strongly influence the capacity reduction and could affect occupant comfort. A reasonable strategy is to precool at 68°F beginning at midnight, allow a 30 min warm-up period before occupancy, and then adjust the occupied set point to 70°F. The zone temperature will then rise above this set point when the chillers are operating at capacity.

Case Study. The control strategy was tested in a 1.4 million square foot office building located near Chicago, Illinois. The facility
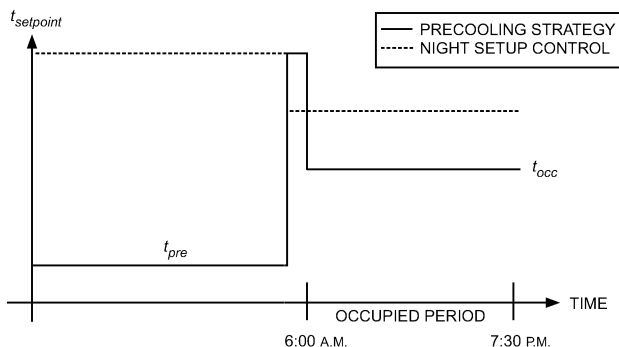
has two identical buildings with very similar internal gains and solar radiation loads, connected by a large, separately cooled entrance area. During tests, the east building used the existing building control strategy and the west building used the precooling strategy.

Four 900 ton vapor compression chillers normally provide chilled water to the air-handling units. Loss of one chiller results in a 25% reduction of the total capacity. This condition was simulated by limiting the vane position of the two chiller units that cool the west building to 75%. The capacity limitation was imposed directly at the chiller control panels. Set points were provided to local zone controllers from a modern energy management and control system. Chiller cooling loads and zone thermal comfort conditions were monitored throughout the tests.

Consistent with simulation predictions, the precooling control strategy successfully limited the peak load to 75% of the cooling capacity for the west building, whereas the east building operated at 100% of capacity. Figure 34 shows the total chiller coil load for the east and west buildings for a week of testing in the middle of August 1995. The cooling-coil load profile on Monday is the most dramatic example of load shifting during this test period. The peak cooling load for this facility often occurs on Monday morning. The cooling limit was achieved on Monday during a period in which a heat emergency had been declared in the city. The severe ambient conditions were compounded by a power outage that caused a loss of the west-side chiller units for approximately 20 min. Under these demanding conditions, the precooling strategy maintained occupant comfort while successfully limiting cooling demand of the west side of the building to less than 75% of that for the east side.

The east-side cooling requirement was at or below the 75% chiller capacity target for Tuesday through Friday, so the emergency precooling strategy was not necessary. For these off-design days, the emergency strategy was not effective in reducing the on-peak cooling requirements because discharge of the mass was not initiated when capacity was below the target. The thermal mass remained charged so that peak reduction would occur if the target value on the off-design days were reset to a lower value.

Precooling the top floor of the facility had already been implemented into the conventional control strategy used for the east building. This was necessary to maintain comfort conditions with full cooling capacity on hot days. As a result, even greater peak reduction would have been recorded if the precool strategy had been compared with conventional night setup control. The total electrical use was greater for the precooled west building; however, the strategy was designed for an emergency and does not attempt to minimize costs.

Fig. 33 Zone Air Temperature Set Points
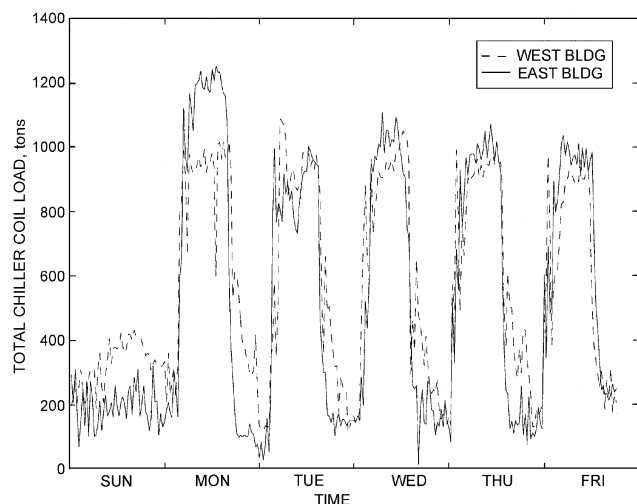
Fig. 34 Total Coil Load for East and West Chiller Units

This emergency strategy should only be applied on days when the available cooling capacity is not sufficient to maintain comfort conditions when using night setup control. Otherwise, the costs of providing cooling could increase significantly. Ongoing ASHRAE research (RP-1313) is seeking to develop simplified strategies for optimal control of building zone set points to minimize operating costs.

CONTROL OF COOL THERMAL STORAGE

The choice of a control strategy for a thermal storage system results from a tradeoff between performance (i.e., operating costs) and ease of implementation (i.e., initial costs). Chiller-priority control has the lowest implementation costs, but generally leads to the highest operating costs. Storage-priority strategies provide superior performance, but require the use of a forecaster and a measurement of state of charge for storage. This section presents details of chiller-priority, load-limiting, and rule-based control applied to ice storage systems. Each of these strategies shares the same procedures for charging storage, but differs in the manner in which storage is discharged. In general, the control strategies presented in this section are appropriate for systems with utility rate structures that include time-of-use energy and demand charges, but would not be appropriate in conjunction with real-time pricing. Additional information on control strategies for cool storage systems can be found in Chapter 34.

Charging Strategies

Ice making should be initiated when both the building is unoccupied and off-peak electrical rates are in effect. During the ice-making period, the chiller should operate at full capacity. Cooling plants for ice storage generally operate most efficiently at full load because of the auxiliaries and the characteristics of ice-making chillers. With feedback control of the chilled-water/glycol supply temperature, full capacity control is accomplished by establishing a low enough set point to ensure this condition (e.g., 20°F).

Internal Melt Storage Tanks. The chiller should operate until the tank reaches its maximum state of charge or the charging period (i.e., off-peak, unoccupied period) ends. This strategy ensures that sufficient ice will be available for the next day without the need for a forecaster. Typically, only a small heat transfer penalty is associated with restoring a partially discharged, internal melt storage tank to a full charge. For this type of storage device, the charging cycle always starts with a high transfer effectiveness because water surrounds the tubes regardless of the amount of ice melted. The heat transfer effectiveness drops gradually until the new ice formations intersect with old formations, at which point the tank is fully recharged.

External Melt Storage Tanks. These tanks have a more significant heat transfer penalty associated with recharging after a partial discharge, because ice forms on the outside of existing formations during charging. In this case, it is more efficient to fully discharge the tank each day and only recharge as necessary to meet the next day's cooling requirements. To ensure that adequate ice is available, the maximum possible storage capacity needed for the next day must be forecast. The storage requirements for the next day depend on the discharge strategy used and the building load. In general, the state of charge for storage necessary to meet the next day's load can be estimated according to

$$X_{chg} = \sum_{k=1}^{\substack{\text{occupied} \\ \text{period}}} \frac{\hat{Q}_{load,k} - \hat{Q}_{ch,k}}{C_s} \qquad (32)$$

where X_{chg} is the relative state of charge at the end of the charging period, C_s is the maximum change in internal energy of the storage tank that can occur during a normal discharge cycle, and $\hat{Q}_{load,k}$ and $\hat{Q}_{ch,k}$ are forecasts of the building load and chiller cooling requirement for the kth stage (e.g., hour) of the occupied period. The

relative state of charge is defined in terms of two reference states: the fully discharged and fully charged conditions that correspond to values of zero and one. These conditions are defined for a given storage based on its particular operating strategy (ASHRAE *Standard* 150; Elleson 1996). The fully charged condition exists when the control stops the charge cycle as part of its normal sequence. Similarly, the fully discharged condition is the point where no more usable cooling is recovered from the tank. Typically, zero state of charge corresponds to a tank of water at a uniform temperature of 32°F and a complete charge is associated with a tank having maximum ice build at 32°F. (The fully discharged and fully charged conditions are arbitrarily selected reference states.) In abnormal circumstances, a storage tank can be discharged or charged beyond these conditions, resulting in relative states of charge below zero or above one.

Hourly forecasts of the next day's cooling requirement can be determined using the algorithm described in the section on Forecasting Diurnal Energy Requirements. However, long-term forecasts are highly uncertain and a safety factor based on previous forecast errors is appropriate (e.g., uncertainty of two or three times the standard deviation of the errors of previous forecasts). Estimates of hourly chiller requirements should be determined using the intended discharge strategy (described in the next section) and building load forecasts.

Discharging Strategies

Three discharge strategies are presented for use with utility structures having on-peak and off-peak energy and demand charges: (1) chiller-priority control, (2) storage-priority, load-limiting control, and (3) a rule-based strategy that uses both chiller-priority and load-limiting strategies.

Chiller-Priority Discharge. During the storage discharge mode, the chiller operates at full cooling capacity (or less if sufficient to meet the load) and storage matches the difference between the building requirement and chiller capacity. For the example system illustrated in Figure 14, the chiller supply temperature set point t_{chws} is set equal to the desired supply temperature for the coils t_{coil}. If the capacity of the chiller is sufficient to maintain this set point, then storage is not used and the system operates in the direct chiller mode. Otherwise, the storage control valve modulates the flow through storage to maintain the supply set point, providing a cooling rate that matches the difference between the building load and the maximum cooling capacity of the chillers.

This strategy is easy to implement and does not require a load forecast. It works well for design conditions, but can result in relatively high demand and energy costs for off-design conditions because the chiller operates at full capacity during the on-peak period.

Storage-Priority, Load-Limiting Control. Several storage-priority control approaches ensure that storage is not depleted prematurely. Braun (1992) presented a storage-priority control strategy, termed *load-limiting* control, which tends to minimize the peak cooling plant power demand. The operation of equipment for load-limiting control during different parts of the occupied period can be described as follows:

- **Off-Peak, Occupied Period.** During this period, the goal is to minimize use of storage, and the chiller-priority described in the previous section should be applied.
- **On-Peak, Occupied Period.** During this period, the goal is to operate the chillers at a constant load while discharging the ice storage such that the ice is completely melted when the off-peak period begins. This requires use of a building cooling-load forecaster. At each decision interval (e.g., 15 min), the following steps are applied:

  (1) Forecast the total integrated building cooling requirement until the end of the discharging period.

(2) Estimate the state of charge of the ice storage tank from measurements.

(3) At any time, the chiller loading for load-limiting control is determined as

$$\dot{Q}_{LLC} = \text{Max}\left[\frac{\hat{Q}_{load,occ} - (X - X_{min})C_s}{\text{D}t_{on}}, \dot{Q}_{ch,min}\right] \quad (33)$$

where $\hat{Q}_{load,occ}$ is a forecast of the integrated building load for the rest of the on-peak period, Δt_{on} is the time remaining in the on-peak period, X is the current state of charge defined as the fraction of the maximum storage capacity, X_{min} is a minimum allowable state of charge, C_s is the maximum possible energy that could be added to storage during discharge, and $\hat{Q}_{ch,min}$ is the minimum allowable chiller cooling capacity. If the chiller does not need to be operated during the remainder of the occupied, on-peak period, the minimum allowable cooling capacity could be set to zero. Otherwise, the cooling capacity should be set to the minimum at which the chiller can safely operate.

(4) Determine the chiller set-point temperature necessary to achieve the desired loading as

$$t_{chws} = t_{chwr} - \frac{\dot{Q}_{LLC}}{C_{chw}} \quad (34)$$

where t_{chwr} is the temperature of water/glycol returned to the chiller and C_{chw} is the capacitance rate (mass flow times specific heat) of the flow stream.

Hourly forecasts of cooling loads can be determined using the algorithm described in the section on Forecasting Diurnal Energy Requirements. The hourly forecasts are then integrated to give a forecast of the total cooling requirement. To ensure sufficient cooling capacity, a worst-case forecast of cooling requirements could be estimated as the sum of the best forecast and two or three times the standard deviation of the errors of previous forecasts.

Rule-Based Controller. Drees and Braun (1996) presented a rule-based controller that combines elements of chiller-priority and storage-priority strategies, along with a demand-limiting algorithm to achieve near-optimal control. The demand-limiting algorithm requires a measurement of the total building electrical use. A simpler strategy is described here that does not require this measurement and yields equivalent performance whenever the peak demand for the billing period is coincident with the peak cooling load.

Figure 35 shows a flowchart for the discharge strategy that is applied during each decision interval (e.g., 15 min) during the occupied period. Block 1 determines whether storage use should be maximized or minimized. Block 2 is used if storage use lowers daily
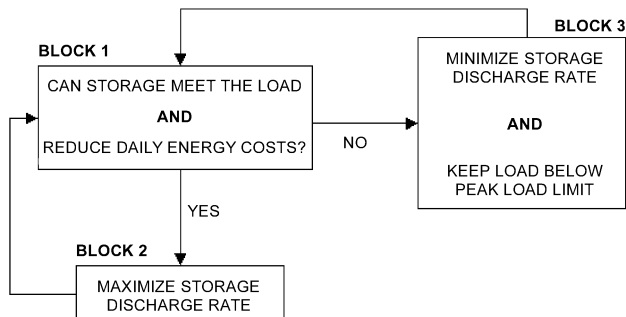
Fig. 35 Flowchart for Rule-Based Controller Discharge Strategy

energy costs and storage is sufficient to meet the remainder of the load for the occupied period without operating the chillers. Otherwise, the goal of the strategy in block 3 is to minimize storage use while keeping peak load below a limit. This strategy tends to keep the chiller(s) heavily loaded (and therefore operating efficiently) until they are no longer needed. The logic in each block is as follows:

• **Block 1: Discharge Strategy Selection.** The discharge of storage will not reduce the energy cost whenever the cost of replenishing the ice is greater than the cost of providing direct cooling by the chiller(s). This situation is always the case during the off-peak, occupied period because the electricity rates are the same as those associated with the charging period and chillers are less efficient in ice-making mode than when providing direct cooling. Furthermore, during the on-peak, occupied period, using storage generally reduces energy costs whenever the following criterion holds:

$$\text{ECR} > \text{COP}_d/\text{COP}_c \quad (35)$$

where ECR is the ratio of on-peak to off-peak energy charges and COP_d and COP_c are coefficients of performance for the cooling plant (including chiller, pumps, and cooling tower fans) during discharging and charging of the tank. The COPs should be evaluated at the worst-case charging and discharging conditions associated with the design day. Typically, this ratio is between about 1.2 and 1.8 for systems with cooling towers. However, the ratio can be lower because of the effect of cool nighttime temperatures, especially for systems with air-cooled condensers in dry climates.

If the criterion of Equation (35) is satisfied, control switches from chiller-priority to storage-priority strategy whenever storage capacity is greater than the remaining integrated load. Therefore, storage-priority control is enabled whenever

$$(X - X_{min})C_s \geq \hat{Q}_{load,occ} \quad (36)$$

Hourly forecasts of cooling loads can be determined using the algorithm described in the section on Forecasting Diurnal Energy Requirements and then integrated to give a forecast of the total cooling requirement. To ensure that adequate ice is available, worst-case hourly forecasts can be determined by adding the expected value of the hourly forecasts and the forecast errors associated with a specified confidence interval (e.g., two standard deviations for a 95% confidence interval). The worst-case hourly forecasts can then be integrated to give a worst-case integrated forecast.

• **Block 2: Maximum Use of Storage.** In this mode, the chillers are turned off and storage is used to meet the entire load throughout the remainder of the occupied period. However, a chiller may need to be turned on if the storage discharge rate is not sufficient to meet the building load (i.e., the coil supply temperature set point can not be maintained).

• **Block 3: Minimize Use of Storage with Peak Load Limiting.** At any time, a target chiller load is determined as

$$\dot{Q}_{ch} = \text{Min}[\text{Max}(\dot{Q}_{ch,peak}, \dot{Q}_{LCC}), \dot{Q}_{load}] \quad (37)$$

where $\dot{Q}_{ch,peak}$ is the peak chiller cooling requirement that has occurred during the on-peak period for the current billing period, $\dot{Q}_{LCC}$ is the chiller load associated with load-limiting control and determined with Equation (33), and $\dot{Q}_{load}$ is the current building load. The chiller set-point temperature necessary to achieve the desired loading is determined as

$$t_{chws} = \text{Max}\left(t_{chwr} - \frac{\dot{Q}_{ch}}{C_{chw}}, t_{coil}\right) \quad (38)$$

On the first day of each billing period, $\dot{Q}_{ch,peak}$ is set to zero. For this first day, applying Equation (37) leads to the load-limiting control strategy described in the previous section. On subsequent days, load-limiting control is used only if the current peak limit would lead to premature depletion of storage. Whenever the current load is less than $\dot{Q}_{ch,peak}$ and $\dot{Q}_{LCC}$, Equations (37) and (38) lead to chiller-priority control.

FORECASTING DIURNAL ENERGY REQUIREMENTS

As discussed previously, forecasts of cooling requirements and electrical use in buildings are often necessary for the control of thermal storage to shift electrical use from on-peak to off-peak periods. In addition, forecasts can help plant operators anticipate major changes in operating modes, such as bringing additional chillers online.

In most methods, predictions are estimated as a function of time-varying input variables that affect cooling requirements and electrical use. Examples of inputs that affect building energy use include (1) ambient dry-bulb temperature, (2) ambient wet-bulb temperature, (3) solar radiation, (4) building occupancy, and (5) wind speed. Methods that include time-varying measured input variables are often termed **deterministic methods**.

Not all inputs affecting cooling requirements and electric use are easily measured. For instance, building occupancy is difficult to determine and solar radiation measurements are expensive. In addition, the accuracy of forecast models that use deterministic inputs depends on the accuracy of future predictions of the inputs. As a result, most inputs that affect building energy use are typically not used.

Much of the time-dependent variation in cooling loads and electrical use for a building can be captured with time as a deterministic input. For instance, building occupancy follows a regular schedule that depends on time of day and time of year. In addition, variations in ambient conditions follow a regular daily and seasonal pattern. Many forecasting methods use time in place of unmeasured deterministic inputs in a functional form that captures the average time dependence of the variation in energy use.

A deterministic model has limited accuracy for forecasts because of both unmeasured and unpredictable (random) input variables. Short-term forecasts can be improved significantly by adding previous values of deterministic inputs and previous output measurements (cooling requirements or electrical use) as inputs to the forecasting model. The time history of these inputs provides valuable information about recent trends in the time variation of the forecasted variable and the unmeasured input variables that affect it. Most forecasting methods use historical variables to predict the future.

Any forecasting method requires that a functional form is defined and the parameters of the model are learned based on measured data. Either offline or online methods can be used to estimate parameters. Offline methods involve estimating parameters from a batch of collected data. Typically, parameters are determined by minimizing the sum of squares of the forecast errors. The parameters of the process are assumed to be constant over time in the offline methods. Online methods allow the parameters of the forecasting model to vary slowly with time. Again, the sum of squares of the forecast errors is minimized, but sequentially or recursively. Often, a forgetting factor is used to give additional weight to the recent data. The ability to track time-varying systems can be important when forecasting cooling requirements or electricity use in buildings, because of the influence of seasonal variations in weather.

Forrester and Wepfer (1984) presented a forecasting algorithm that uses current and previous ambient temperatures and previous loads to predict future requirements. Trends on an hourly time scale are accounted for with measured inputs for a few hours preceding the current time. Day-to-day trends are considered by using the value of the load that occurred 24 h earlier as an input. One of the major

limitations of this model is its inability to accurately predict loads when an occupied day (e.g., Monday) follows an unoccupied (e.g., Sunday) or when an unoccupied day follows an occupied day (e.g., Saturday). The cooling load for a particular hour of the day on a Monday depends very little on the requirement 24 h earlier on Sunday. Forrester and Wepfer (1984) described a number of methods for eliminating this 24 h indicator. MacArthur et al. (1989) also presented a load profile prediction algorithm that uses a 24 h regressor.

Armstrong et al. (1989) presented a very simple method for forecasting either cooling or electrical requirements that does not use the 24 h regressor; Seem and Braun (1991) further developed and validated this method. The "average" time-of-day and time-of-week trends are modeled using a lookup table with time and type of day (e.g., occupied versus unoccupied) as the deterministic input variables. Entries in the table are updated using an exponentially weighted, moving-average model. Short-term trends are modeled using previous hourly measurements of cooling requirements in an autoregressive (AR) model. Model parameters adapt to slow changes in system characteristics. The combination of updating the table and modifying model parameters works well in adapting the forecasting algorithm to changes in season and occupancy schedule.

Kreider and Wang (1991) used artificial neural networks (ANNs) to predict energy consumption of various HVAC equipment in a commercial building. Data inputs to the ANN included (1) previous hour's electrical power consumption, (2) building occupancy, (3) wind speed, (4) ambient relative humidity, (5) ambient dry-bulb temperature, (6) previous hour's ambient dry-bulb temperature, (7) two hours' previous ambient temperature, and (8) sine and cosine of the hour number to roughly represent the diurnal change of temperature and solar insolation. The primary purpose in developing these models was to detect changes in equipment and system performance for monitoring purposes. However, the authors suggested that an ANN-based predictor might be valuable when used to predict energy consumption with a network based on recent historical data. Forecasts of all deterministic input variables are necessary to apply this method.

Gibson and Kraft (1993) used an ANN to predict building electrical consumption as part of the operation and control of a thermal energy storage (TES) cooling system. The ANN used the following inputs: (1) electric demand of occupants (lighting and other loads), (2) electric demand of TES cooling tower fans, (3) outside ambient temperature, (4) outside ambient temperature/inside target temperature, (5) outside ambient relative humidity, (6) on/off status for building cooling, (7) cooling system on/off status, (8) chiller #1 direct-cooling mode on/off status, (9) chiller #2 direct-cooling mode on/off status, (10) ice storage discharging mode on/off status, (11) ice storage charging mode on/off status, (12) chiller #1 charging mode on/off status, and (13) chiller #2 charging mode on/off status. To use this forecaster, values of each of these inputs must be predicted. Although the authors suggest that average occupancy demand profile be used as an input, they do not state how the other input variables should be forecast.

A Forecasting Algorithm

This section presents an algorithm for forecasting hourly cooling requirements or electrical use in buildings that is based on the method developed by Seem and Braun (1991). At a given hour n, the forecast value is

$$\hat{E}(n) = \hat{X}(n) + \hat{D}(h,d) \tag{39}$$

where

$\hat{E}(n)$ = forecast cooling load or electrical use for hour n

$\hat{X}(n)$ = stochastic or probabilistic part of forecast for hour n

$\hat{D}(h,d)$ = deterministic part of forecast at hour n associated with hth hour of day and current day type d

The deterministic part of the forecast is simply a lookup table for the forecasted variable in terms of hour of day h and type of day d. Seem and Braun recommend using three distinct day types: unoccupied days, occupied days following unoccupied days, and occupied days following occupied days. The three day types account for differences between the building responses associated with return from night setup and return from weekend setup. The building operator or control engineer must specify the number of day types and a calendar of day types.

Given the hour of day and day type, the deterministic part of the forecast is simply the value stored in that location in the table. Table entries are updated when a new measurement becomes available for that hour and day type. Updates are accomplished through the use of an exponentially weighted, moving-average (EWMA) model as

$$\hat{D}(h,d) = \hat{D}(h,d)_{old} + \lambda[E(n) - \hat{D}(h,d)_{old}] \qquad (40)$$

where

$\quad E(n)$ = measured value of cooling load or electrical use for current hour n
$\quad \lambda$ = exponential smoothing constant, $0 < \lambda < 1$
$\hat{D}(h,d)_{old}$ = previous table entry for $\hat{D}(h,d)$

As λ increases, the more recent observations have more influence on the average. As λ approaches zero, the table entry approaches the average of all data for that hour and day type. When λ equals one, the table entry is updated with the most recent measured value. Seem and Braun recommend using a value of 0.30 for λ in conjunction with three day types and 0.18 with two day types.

The stochastic portion of the forecast is estimated with a third-order autoregressive model, AR(3), of forecasting errors associated with the deterministic model. With this model, an estimate of the next hour's error in the deterministic model forecast is given by the following equation:

$$\hat{X}(n+1) = \phi_1 X(n) + \phi_2 X(n-1) + \phi_3 X(n-2) \qquad (41)$$

where

$\quad X(n)$ = difference between measurement and deterministic forecast of cooling load or electrical use at any hour n
ϕ_1, ϕ_2, ϕ_3 = parameters of AR(3) model that must be learned

The error in the deterministic forecast at any hour is simply

$$X(n) = E(n) - \hat{D}(h,d) \qquad (42)$$

For forecasting more than one hour ahead, conditional expectation is used to estimate the deterministic model forecast errors using the AR(3) model as follows:

$$\hat{X}(n+2) = \phi_1\hat{X}(n+1) + \phi_2 X(n) + \phi_3 X(n-1)$$

$$\hat{X}(n+3) = \phi_1\hat{X}(n+2) + \phi_2\hat{X}(n+1) + \phi_3 X(n)$$

$$\vdots$$

$$\hat{X}(n+k) = \phi_1\hat{X}(n+k+1) + \phi_2\hat{X}(n+k-2)$$
$$+ \phi_3\hat{X}(n+k-3) \qquad \text{for } k > 3 \qquad (43)$$

Online estimation of the AR(3) model parameters is accomplished by minimizing the following time-dependent cost function:

$$J(\phi) = \sum_{k=1}^{n} \alpha^{n-k}[X(k) - \hat{X}(k)]^2 \qquad (44)$$
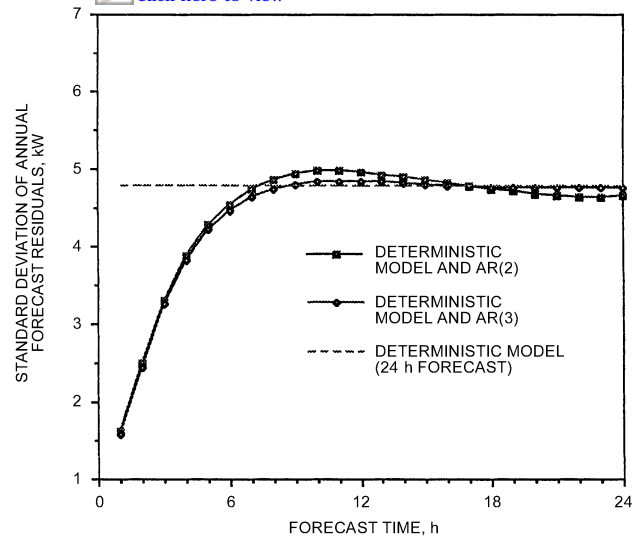
**Fig. 36   Standard Deviation of Annual Errors
for 1 to 24 h Ahead Forecasts**

where the constant α is called the forgetting factor and has a value between 0 and 1. With this formulation, the residual for the current time step has a weight of one and the residual for k time steps back has a weight of α_k. By choosing a value of α that is positive and less than one, recent data have greater influence on the parameter estimates. In this manner, the model can track changes caused by seasonal or other effects. Seem and Braun recommend using a forgetting factor of 0.99. Parameters of the AR(3) model should be updated at each hour when a new measurement becomes available.

Ljung and Söderström (1983) describe online estimation methods for determining coefficients of an AR model. The parameter estimates should be evaluated for stability. If an AR model is not stable, then the forecasts will grow without bound as the time of forecasts increases. Ljung and Söderström discuss methods for checking stability.

Seem and Braun compared forecasts of electrical usage with both simulated and measured data. Figure 36 shows the standard deviation of the 1 h through 24 h errors in electrical use forecasts for annual simulation results. Results are given for the deterministic model alone, deterministic plus AR(2), and deterministic plus AR(3). For the combined models, the standard deviation of the residuals increases as the forecast length increases. For short time steps (i.e., less than 6 h), the combined deterministic and stochastic models provide much better forecasts than the purely deterministic model (i.e., lookup table).

Seem and Braun also investigated a method for adjusting the deterministic forecast based on using weather service forecasts of maximum daily ambient temperature as an input. For short periods (i.e., less than 4 h), forecasts for the temperature-dependent model were nearly identical to forecasts for the temperature-independent model. For longer periods, the temperature-dependent model provided better forecasts than the temperature-independent model.

CONTROL OPTIMIZATION METHODS

STATIC OPTIMIZATION

Optimal supervisory control of cooling equipment involves determining the control that minimizes the total operating cost. For an all-electric system without significant storage, cost optimization leads to minimization of power at each instant in time. Optimal control does depend on time, through changing cooling requirements and ambient conditions. Static optimization techniques applied to a
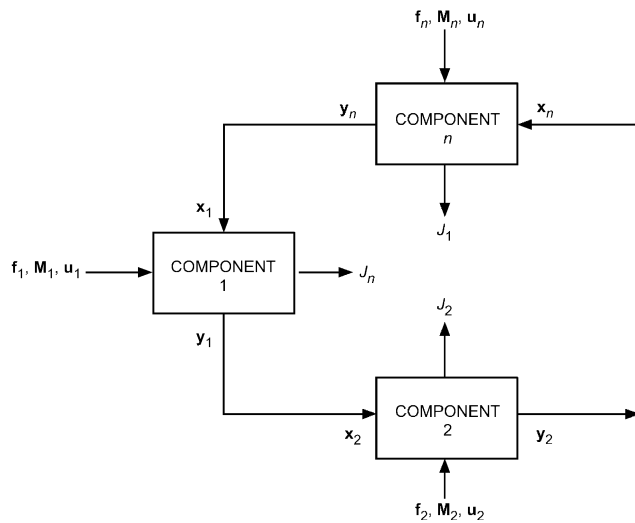
Fig. 37 Schematic of Modular Optimization Problem

general simulation can be used to determine optimal supervisory control variables. The simulation may be based on physical or empirical models. However, for control variable optimization, empirical and semiempirical models are often used where variables are estimated from measurements. This section presents a framework for determining optimal control and a simplified approach for estimating control laws for cooling plants.

General Static Optimization Problem

Figure 37 depicts the general nature of the static optimization problem for a system of interconnected components. Each component in a system is represented as a separate set of mathematical relationships organized into a computer model. Its output variables and operating cost are functions of parameter, input, output, uncontrolled, and controlled variables. The structure of the complete set of equations to be solved for the entire system is dictated by the manner in which the components are interconnected.

The problem is formally stated as the minimization of the sum of the operating costs of each component J_i with respect to all discrete and continuous controls or

Minimize

$$J(\mathbf{f}, \mathbf{M}, \mathbf{u}) = \sum_{i=1}^{n} J_i(\mathbf{x}_i, \mathbf{y}_i, \mathbf{f}_i, \mathbf{M}_i, \mathbf{u}_i) \tag{45}$$

with respect to $\mathbf{M}$ and $\mathbf{u}$, subject to equality constraints of the form

$$\mathbf{g}(\mathbf{f}, \mathbf{M}, \mathbf{u}) = \begin{bmatrix} \mathbf{g}_1(\mathbf{f}_1, \mathbf{M}_1, \mathbf{u}_1, \mathbf{x}_1, \mathbf{y}_1) \\ \mathbf{g}_2(\mathbf{f}_2, \mathbf{M}_2, \mathbf{u}_2, \mathbf{x}_2, \mathbf{y}_2) \\ \vdots \\ \mathbf{g}_n(\mathbf{f}_n, \mathbf{M}_n, \mathbf{u}_n, \mathbf{x}_n, \mathbf{y}_n) \end{bmatrix} = 0 \tag{46}$$

and inequality constraints of the form

$$\mathbf{h}(\mathbf{f}, \mathbf{M}, \mathbf{u}) = \begin{bmatrix} h_1(\mathbf{f}_1, \mathbf{M}_1, \mathbf{u}_1, \mathbf{x}_1, \mathbf{y}_1) \\ h_2(\mathbf{f}_2, \mathbf{M}_2, \mathbf{u}_2, \mathbf{x}_2, \mathbf{y}_2) \\ \vdots \\ h_n(\mathbf{f}_n, \mathbf{M}_n, \mathbf{u}_n, \mathbf{x}_n, \mathbf{y}_n) \end{bmatrix} \geq 0 \tag{47}$$

where, for any component i,
    $\mathbf{x}_i$ = vector of input stream variables
    $\mathbf{y}_i$ = vector of output stream variables

    $\mathbf{f}_i$ = vector of uncontrolled variables
    $\mathbf{M}_i$ = vector of discrete control variables
    $\mathbf{u}_i$ = vector of continuous control variables
    J_i = operating cost
    $\mathbf{g}_i$ = vector of equality constraints
    h_i = vector of inequality constraints

Typical input and output stream variables for thermal systems are temperature and mass flow rate. Uncontrolled variables are measurable quantities that may not be controlled, but that affect component outputs and/or costs, such as ambient dry- and wet-bulb temperature.

Both equality and inequality constraints arise in the optimization of chilled-water systems. One example of an equality constraint that arises when two or more chillers are in operation is that the sum of their loads must equal the total load. The simplest type of inequality constraint is a bound on a control variable. For example, lower and upper limits are necessary for the chilled-water set temperature, to avoid freezing in the evaporator and to provide adequate dehumidification for the zones. Any equality constraint may be rewritten in the form of Equation (46) such that when it is satisfied, the constraint equation is equal to zero. Similarly, inequality constraints may be expressed as Equation (47), so that the constraint equation is greater than or equal to zero to avoid violation.

Braun (1988) and Braun et al. (1989b) presented a component-based nonlinear optimization and simulation tool and used it to investigate optimal performance. Each component is represented as a separate subroutine with its own parameters, controls, inputs, and outputs. The optimization problem is solved efficiently by using second-order representations for costs that arise from curve-fits or Taylor-series approximations. Application of the component-based optimization led to many guidelines for control and a simplified system-based optimization methodology. In particular, the results showed that optimal set points could be correlated as a linear function of load and ambient wet-bulb temperature.

Cumali (1988) presented a method for real-time global optimization of HVAC systems, including the central plant and associated piping and duct networks. The method uses a building load model for the zones based on (Winkelman et al. 1993) a coupled weighting-factor method similar to that used in DOE-2. Variable time steps are used to predict loads over a 5 to 15 min period. The models are based on thermodynamic, heat transfer, and fluid mechanics fundamentals and are calibrated to match actual performance, using data obtained from the building and plant. Pipe and duct networks are represented as incidence and circuit matrices, and both dynamic and static losses are included. Coupling fluid energy transfers with zone loads is done using custom weighting factors calibrated for each zone. The resulting equations are grouped to represent feasible equipment allocations for each range of building loads, and solved using a nonlinear solver. The objective function is the cost of delivering or removing energy to meet the loads, and is constrained by the comfort criteria for each zone. The objective function is minimized using the reduced gradient method, subject to constraints on comfort and equipment operation. Optimization starts with the feasible points as determined by a nonlinear equation solver for each combination of equipment allocation. The values of set points that minimize the objective function are determined; the allocation with the least cost is the desired operation mode. Results obtained from this approach have been applied to high-rise office buildings in San Francisco with central plants, VAV, dual-duct, and induction systems. Electrical demand reductions of 8 to 12% and energy savings of 18 to 23% were achieved.

Simplified System-Based Optimization Approach

The component-based optimization method presented by Braun et al. (1989b) was used to develop a simpler method for determining optimal control. The method involves correlating overall cooling plant power consumption using a quadratic functional form. Minimizing this function leads to linear control laws for control variables

in terms of uncontrolled variables. The technique may be used to tune parameters of the cooling tower and chilled-water reset strategies presented in the section on Supervisory Control Strategies and Tools. It may also be used to define strategies for supply air temperature reset for VAV systems and flow control for variable-speed condenser water pumps.

In the vicinity of any optimal control point, plant power consumption may be approximated as a quadratic function of the continuous control variables for each operating mode (i.e., discrete control mode). A quadratic function also correlates power consumption in terms of uncontrolled variables (e.g., load, ambient temperature) over a wide range of conditions. This leads to the following general functional relationship between overall cooling plant power and the controlled and uncontrolled variables:

$$J(\mathbf{f}, \mathbf{M}, \mathbf{u}) = \mathbf{u}^T \mathbf{A} \mathbf{u} + \mathbf{b}^T \mathbf{u} + \mathbf{f}^T \mathbf{C} \mathbf{f} + \mathbf{d}^T \mathbf{f} + \mathbf{f}^T \mathbf{E} \mathbf{u} + g \qquad (48)$$

where J is the total plant power, $\mathbf{u}$ is a vector of continuous and free control variables, $\mathbf{f}$ is a vector of uncontrolled variables, $\mathbf{M}$ is a vector of discrete control variables, and the superscript T designates the transpose vector. $\mathbf{A}$, $\mathbf{C}$, and $\mathbf{E}$ are coefficient matrices, $\mathbf{b}$ and $\mathbf{d}$ are coefficient vectors, and g is a scalar. The empirical coefficients of this function depend on the operating modes so that these constants must be determined for each feasible combination of discrete control modes.

A solution for the optimal control vector that minimizes power may be determined analytically by applying the first-order condition for a minimum. Equating the Jacobian of Equation (48) with respect to the control vector to zero and solving for the optimal control set points gives

$$\mathbf{u}^* = \mathbf{k} + \mathbf{K} \mathbf{f} \qquad (49)$$

where

$$\mathbf{k} = -\mathbf{A}^{-1} \mathbf{b}/2 \qquad (50)$$

$$\mathbf{K} = -\mathbf{A}^{-1} \mathbf{E}/2 \qquad (51)$$

The cost associated with the unconstrained control of Equation (49) is

$$J^* = \mathbf{f}^T \boldsymbol{\theta} \mathbf{f} + \boldsymbol{\sigma}^T \mathbf{f} + \tau \qquad (52)$$

where

$$\boldsymbol{\theta} = \mathbf{K}^T \mathbf{A} \mathbf{k} + \mathbf{E} \mathbf{K} + \mathbf{C} \qquad (53)$$

$$\boldsymbol{\sigma} = 2 \mathbf{K} \mathbf{A} \mathbf{k} + \mathbf{K} \mathbf{b} + \mathbf{E} \mathbf{k} + \mathbf{d} \qquad (54)$$

$$\tau = \mathbf{K}^T \mathbf{A} \mathbf{k} + \mathbf{b}^T \mathbf{k} + g \qquad (55)$$

The control defined by Equation (49) results in a minimum power consumption if $\mathbf{A}$ is positive definite. If this condition holds and if the system power consumption is adequately correlated with Equation (48), then Equation (49) dictates that the optimal continuous, free control variables vary as a nearly linear function of the uncontrolled variables. However, a different linear relationship applies to each feasible combination of discrete control modes. The minimum cost associated with each mode combination must be computed from Equation (52) and compared to identify the minimum.

Uncontrolled Variables. As discussed in the background section, optimal control variables primarily depend on ambient wet-bulb temperature and total chilled-water load. The load affects the heat transfer requirements for all heat exchangers, whereas the wet-bulb temperature affects chilled- and condenser water temperatures necessary to achieve a given heat transfer rate. As discussed in the section on Supervisory Control Strategies and Tools, cooling coil heat transfer depends on the coil entering wet-bulb temperature. However, this reduces to an ambient wet-bulb temperature dependence for a given ventilation mode (e.g., minimum outside air or economizer) and fixed zone conditions. Thus, separate cost functions are necessary for each ventilation mode, with load and ambient wet bulb as uncontrolled variables. Alternatively, for a specified ventilation strategy (e.g., the economizer strategy from the section on Supervisory Control Strategies and Tools), three uncontrolled variables could be used for all ventilation modes: load, ambient wet-bulb temperature, and average cooling-coil inlet wet-bulb temperature.

Additional uncontrolled variables that could be important if varied over a wide range are the individual zone latent-to-sensible load ratios and ratios of individual sensible zone loads to total sensible loads for all zones. However, these variables are difficult to determine from measurements and are of secondary importance.

Free Control Variables. The number of independent or "free" control variables in the optimization can be reduced significantly by using the simplified strategies presented in the section on Supervisory Control Strategies and Tools. For instance, the optimal static pressure set point for a VAV system should keep at least one VAV box fully open and should not be considered as a free optimization variable. Similarly, supply air temperature for a CAV system should be set to minimize reheat. Additional near-optimal guidelines were presented for sequencing of cooling tower fans, sequencing of chillers, loading of chillers, reset of pressure differential set point for variable-speed pumping, and chilled-water reset with fixed-speed pumping. Furthermore, Braun et al. (1989a) showed that using identical supply air set points for multiple air handlers gives near-optimal results for VAV systems.

For all variable-speed auxiliary equipment (i.e., pumps and fans), the free set-point variables to use in Equation (48) could be reduced to the following: (1) supply air set temperature, (2) chilled-water set temperature, (3) tower airflow relative to design capacity, and (4) condenser water flow relative to design capacity. All other continuous supervisory control variables are dependent on these variables with the simplified strategies presented in the section on Supervisory Control Strategies and Tools.

Some dependent control variables may be discrete control variables. For instance, variable-flow pumping may be implemented with multiple fixed- and variable-speed pumps where the number of operating pumps is a discrete variable that changes when a variable-speed pump reaches its capacity. These discrete changes could lead to discrete changes in cost because of changes in overall pump efficiency. However, this has a relatively small effect on overall power consumption and may be neglected in fitting the overall cost function to changes in the control variables.

Some discrete control variables may also be independent variables. In general, different cost functions arise for all operating modes consisting of each possible combination of discrete control variables. With all variable-speed pumps and fans, the only significant discrete control variable is the number of operating chillers. Then, optimization involves determining optimal values of only four continuous control variables for each of the feasible chiller modes. A chiller mode defines which of the available chillers are to be online. The chiller mode giving the minimum overall power consumption represents the optimum. For a chiller mode to be feasible, the specified chillers must operate safely within their capacity and surge limits. In practice, abrupt changes in the chiller modes should also be avoided. Large chillers should not be cycled on or off except when the savings associated with the change are significant.

Using fixed-speed equipment reduces the number of free continuous control variables. For instance, supply air temperature is removed as a control variable for CAV systems, and chilled-water temperature is not included for fixed-speed chilled-water pumping. However, for multiple chilled-water pumps not dedicated to chillers, the number of operating pumps can become a free discrete control variable. Similarly, for multiple fixed-speed cooling tower fans and condenser water pumps, each of the discrete combinations can

be considered as a separate mode. However, for multiple cooling tower cells with multiple fan speeds, the number of possible combinations may be large. A simpler approach that works satisfactorily is to treat relative flows as continuous control variables during optimization and to select the discrete relative flow that is closest to the optimal value. At least three relative flows (discrete flow modes) are necessary for each chiller mode to fit the quadratic cost function. The number of possible sequencing modes for fixed-speed pumps is generally much more limited than that for cooling tower fans, with two or three possibilities (at most) for each chiller mode. In fact, with many current designs, individual pumps are physically coupled with chillers, and it is impossible to operate more or fewer pumps than the number of operating chillers. Thus, it is generally best to treat the control of fixed-speed condenser water pumps with a set of discrete control possibilities rather than use a continuous control approximation.

Training. The coefficients of Equation (48) must be determined empirically, and various approaches have been proposed. One approach is to apply regression techniques directly to measurements of total power consumption. Because the cost function is linear with respect to the empirical coefficients, linear regression techniques may be used. A set of experiments can be performed over the expected range of operating conditions. Large amounts of data that include the entire range must be taken to account for measurement uncertainty. The regression could possibly be performed online using least-squares recursive parameter updating (Ljung and Söderström 1983). However, precautions should be taken to ensure that the matrix **A** is positive definite, which guarantees a minimum. If system power is relatively flat, automated methods could generate coefficients that produce a maximum in power consumption rather than a minimum (Brandemuehl and Bradford 1998).

Rather than fitting empirical coefficients of the system-cost function of Equation (48), the coefficients of the optimal control Equation (49) and the minimum-cost function of Equation (52) may be estimated directly. At a limited set of conditions, optimal values of the continuous control and free variables may be estimated through trial-and-error variations. Only three independent conditions are necessary to determine coefficients of the linear control law given by Equation (49) if load and wet bulb are the only uncontrolled variables. The coefficients of the minimum cost function can then be determined from system measurements with the linear control law in effect. The disadvantage of this approach is that there is no direct way to handle physical constraints on the controls.

Summary and Constraint Implementation. The methodology for determining the near-optimal control of a chilled-water system may be summarized as follows:

1. Change the chiller operating mode if system operation is at the limits of chiller operation (near surge or maximum capacity).
2. For the current set of conditions (load and wet bulb), estimate the feasible modes of operation that avoid operating the chiller and condenser pump at their limits.
3. For the current operating mode, determine optimal values of the continuous controls using Equation (49).
4. Determine a constrained optimum if controls exceed their bounds.
5. Repeat steps 3 and 4 for each feasible operating mode.
6. Change the operating mode if the optimal cost associated with the new mode is significantly less than that associated with the current mode.
7. Change the values of the continuous control variables. When treating multiple-speed fan control with a continuous variable, use the discrete control closest to the optimal continuous value.

If linear optimal control [Equation (49)] is directly determined from optimal control results, then the constraints on controls may be handled directly. Otherwise, a simple solution is to constrain the individual control variables as necessary and neglect the effects of

the constraints on the optimal values of the other controls and the minimum cost function. The variables of primary concern for constraints are the chilled-water and supply air set temperatures. These controls must be bounded for proper comfort and safe operation of the equipment. On the other hand, cooling tower fans and condenser water pumps should be sized so the system performs efficiently at design loads, and constraints on control of this equipment should only occur under extreme conditions.

The optimal value of the chilled-water supply temperature is coupled to the optimal value of the supply air temperature, so decoupling these variables in evaluating constraints is generally not justified. However, optimization studies indicate that when either control is operated at a bound, the optimal value of the other free control is approximately bounded at a value that depends only on the ambient wet-bulb temperature. The optimal value of this free control (either chilled-water or supply air set point) may be estimated at the load at which the other control reaches its limit. Coupling between optimal values of the chilled-water and condenser water loop controls is not as strong; interactions between constraints on these variables may be neglected.

Case Studies. Braun et al. (1987) correlated the power consumption of the Dallas-Ft. Worth airport chiller, condenser pumps, and cooling tower fans with the quadratic cost function given by Equation (48) and showed good agreement with data. Because the chilled-water loop control was not considered, the chilled-water set point was treated as a known uncontrolled variable. The discrete control variables associated with the four tower cells with two-speed fans and the three condenser pumps were treated as continuous control variables. The optimal control determined by the near-optimal Equation (49) also agreed well with that determined using a nonlinear optimization applied to a detailed simulation of the system.

In subsequent work, Braun et al. (1989b) considered complete system simulations (cooling plant and air handlers) to evaluate the performance of the quadratic, system-based approach. A number of different system characteristics were considered. Figures 20, 25, 38, and 39 show comparisons between the controls as determined with the component-based and system-based methods for a range of loads, for a relatively low and high ambient wet-bulb temperature (60°F and 80°F).

In Figures 25 and 38, optimal values of the chilled-water and supply air temperatures are compared for a system with variable air and water flow. The near-optimal control equation provides a good fit to the optimization results for all conditions considered. The chilled-water temperature was constrained between 38 and 55°F,
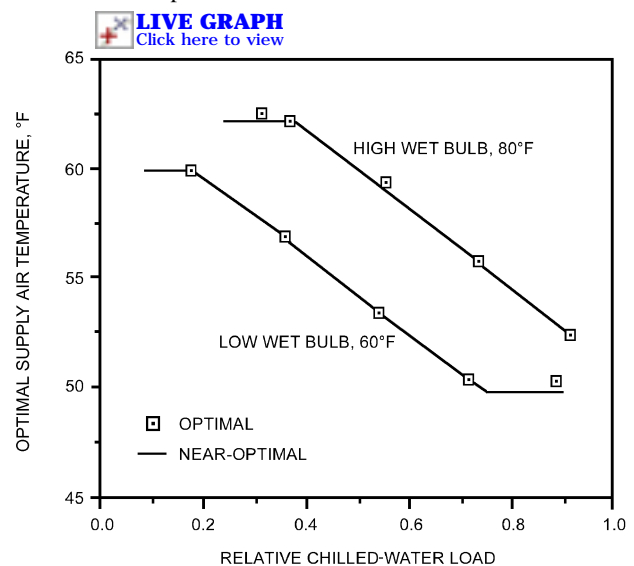
Fig. 38   Comparisons of Optimal Supply Air Temperature
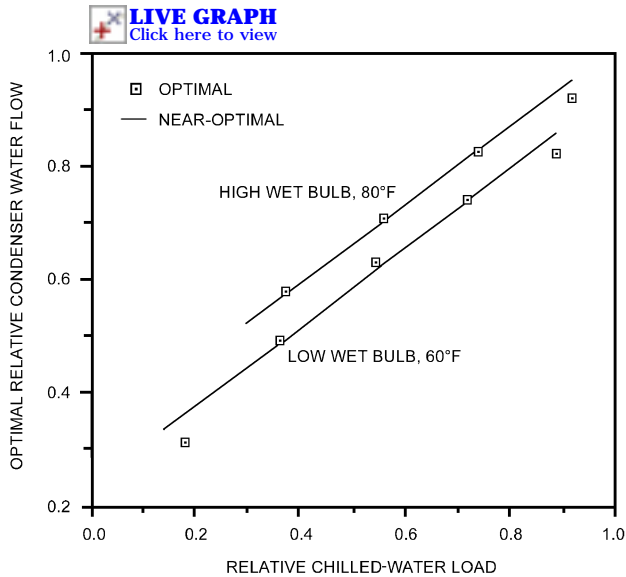
Fig. 39   Comparisons of Optimal Condenser Pump Control

while the supply air set point was allowed to float freely. Figures 25 and 38 show that, for the conditions where the chilled-water temperature is constrained, the optimal supply air temperature is also nearly bounded at a value that depends on the ambient wet bulb.

Optimal relative cooling tower air and condenser water flow rates are compared in Figures 20 and 39 for a system with variable-speed cooling tower fans and condenser water pumps. Although the optimal controls are not exactly linear functions of the load, the linear control equation provides an adequate fit. The differences in these controls result in insignificant differences in overall power consumption, because, as discussed in the background section, the optimum is extremely flat with respect to these variables. The nonlinearity of the condenser loop controls is partly due to the constraints imposed on the chilled-water set temperature. However, this effect is not very significant. Figures 20 and 39 also suggest that the optimal condenser loop control is not very sensitive to ambient wet-bulb temperature.

DYNAMIC OPTIMIZATION

The optimal supervisory control for storage is a complex function of such factors as utility rates, load profile, chiller characteristics, storage characteristics, and weather. For a utility rate structure that includes both time-of-use energy and demand charges, the optimal strategy can depend on variables that extend over a monthly time scale. The overall problem of minimizing the utility cost over a billing period (e.g., a month) can be mathematically described as follows:

Minimize

$$J = \sum_{k=1}^{N} (E_k P_k \, \Delta\tau) + \mathrm{Max}_{1 \le k \le N}(D_k P_k) \qquad (56)$$

with respect to the control variables $(u_1, u_2, \ldots, u_N)$ and subject to the following constraints for each stage k:

$$u_{min,k} \le u_k \le u_{max,k} \qquad (57)$$

$$x_k = f(x_{k-1}, u_k, k) \qquad (58)$$

$$x_{min} \le x_k \le x_{max} \qquad (59)$$

$$x_N = x_0 \qquad (60)$$

where J is the utility cost associated with the billing period (e.g., a month); $\Delta\tau$ is the stage time interval (typically equal to the time window over which demand charges are levied, e.g., 0.25 h); N is the number of time stages in a billing period, and for each stage k, P is the average building electrical power (kW); E is the energy cost rate or cost per unit of electrical energy (\$/kWh); D is the demand charge rate or cost per peak power rate over the billing period (\$/kW); u is the control variable that regulates the rate of energy removal from or addition to storage over the stage; u_{max} is the maximum value for u; u_{min} is the minimum value for u; x is the state of storage at the end of the stage; x_{max} is the maximum admissible state of storage; x_{min} is the minimum admissible state of storage; and f is a state equation that relates the state of storage at stage k to the previous state and current control.

The first and second terms in Equation (56) are the total cost of energy use and building demand for the billing period. Both the energy and demand cost rates can vary with time, but typically have two values associated with on- and off-peak periods. An even more complex cost optimization results if the utility includes ratchet clauses in which the demand charge is the maximum of the monthly peak demand cost and some fraction of the previous monthly peak demand cost during the cooling season. With real-time pricing, the demand charge, which is the second term in Equation (56), might not exist and the hourly energy rates would vary over time according to the generation costs.

For ice or chilled-water storage systems, the control variable could be the rate at which energy is added or removed from storage. In this case, the constraint given by Equation (57) arises from limits that depend on the chiller and storage heat exchanger and can also depend on the state of storage. For use of building thermal mass, the control variable could be the zone temperature(s) and the constraint of Equation (57) would be associated with comfort considerations or capacity constraints. Different comfort limits would probably apply for occupied and unoccupied periods.

The equality constraint of Equation (58) is termed the state equation. The state of storage at any stage k is a function of the previous state (x_{k-1}), the control (u_k), and other time-dependent factors (e.g., ambient temperature). For lumped storage systems (e.g., ice), the state of storage can be characterized with a single-state variable. However, for distributed storage (e.g., a building structure), multiple-state equations may be necessary to properly characterize the dynamics. The state of storage is also constrained to be between states associated with full discharge and full charge [Equation (59)]. The constraint of Equation (60) forces a steady-periodic solution to the problem. This constraint becomes less important as the length of analysis increases.

To determine a control strategy for charging and discharging storage that minimizes utility cost, Equation (56) must be minimized over the entire billing period because of the influence of the demand charge. Alternatively, the optimization problem can be posed as a series of shorter-term (e.g., daily or weekly) optimizations with a constraint on the peak demand charge according to

Minimize

$$J = \sum_{k=1}^{N} \{E_k P_k \, \Delta\tau\} + \mathrm{TDC} \qquad (61)$$

with respect to the control variables $(u_1, u_2, \ldots, u_N)$ and a billing period target demand cost (TDC) and subject to the constraints of Equations (57) through (60) and the following equation:

$$D_k P_k \le \mathrm{TDC} \qquad (62)$$

The constraint expressed in Equation (62) arises from the form of the cost function chosen for Equation (61). At each stage, the

demand cost must be less than or equal to the peak demand cost for the billing period. The peak or **target demand cost (TDC)** is an optimization variable that affects both energy and demand costs. Using Equation (61) rather than Equation (56) simplifies the numerical solution.

Two types of solutions to the optimization problem are of interest: (1) minimum billing-period operating cost and (2) minimum energy cost for a specified target demand cost (TDC) and short-term horizon (e.g., a day). The first problem is useful for benchmarking the best control and minimum cost through simulation, but is not useful for online control because forecasts beyond a day are unreliable. Mathematical models of the building, equipment, and storage can be used to estimate load requirements, power, and state of storage. The second solution can be used for online control in conjunction with a system model and forecaster.

For minimum operating costs (first optimization problem), $N+1$ variables must be determined to minimize the cost function of Equation (61) over the length of the billing period. For a given value of TDC, minimization of Equation (61) with respect to the N charging (and discharging) control variables may be accomplished using dynamic programming (Bellman 1957) or some other direct search method. The primary advantages of dynamic programming are that it handles constraints on both state and control variables in a straightforward manner and also guarantees a global minimum. However, the computation becomes excessive if more than one state variable is needed to characterize storage. The N-variable optimization problem is resolved at each iteration of an outer loop optimization for TDC. Brent's algorithm (1973) is a robust method for solving the one-dimensional optimization for the demand target because it does not require derivative information. This is important because TDC appears as an inequality constraint in the dynamic programming solution and may not always be triggered.

For shorter-term optimizations (second optimization problem), dynamic programming can still be used to minimize Equation (61) with respect to the N charging (and discharging) control variables for a specified TDC. However, an optimal value for TDC cannot be determined when demand charges are imposed. For ice storage, Drees and Braun (1996) found that a simple and near-optimal approach is to set TDC to zero at the beginning of each billing period. Therefore, the optimizer minimizes the demand cost for the first optimization period (e.g., a day) and then uses this demand as the target for the billing period unless it is exceeded. For online optimization, the optimization problem can be resolved at regular intervals (e.g., 1 h) during each day's operation.

Ice Storage Control Optimization

Several researchers have studied optimal supervisory control of ice storage systems. Braun (1992) solved daily optimization problems for two limiting cases: minimum energy (i.e., no demand charge) and minimum demand (no energy charge). Results of the optimizations for different days and utility rates were compared with simple chiller-priority and load-limiting control strategies (see the section on Supervisory Control Strategies and Tools). For the ice-on-pipe system considered, load-limiting control was found to be near optimal for both energy and demand costs with on-peak to off-peak energy cost ratios greater than about 1.4.

Drees and Braun (1996) solved both daily and monthly optimization problems for a range of systems with internal-melt area-constrained ice storage tanks. The optimization results were used to develop rules that became part of a rule-based, near-optimal controller presented in the section on Supervisory Control Strategies and Tools. For a range of partial-storage systems, load profiles, and utility rate structures, the monthly electrical costs for the rule-based control strategy were, on average, within about 3% of the optimal costs.

Henze et al. (1997a) developed a simulation environment that determines the optimal control strategy to minimize operating cost,

including energy and demand charges, over the billing period. A modular cooling plant model was used that includes three compressor types (screw, reciprocating, and centrifugal), three ice storage media (internal melt, external melt, and ice harvester), a water-cooled condenser, central air handler, and all required fans and pumps. The simulation tool was used to compare the performance of chiller-priority, constant-proportion, storage-priority, and optimal control.

Henze et al. (1997b) presented a predictive optimal controller for use with **real-time pricing (RTP)** structures. For the RTP structure considered, the demand term of Equation (61) disappears and the optimization problem only involves a 24 h period. The controller calculates the optimal control trajectory at each time step (e.g., 30 min), executes the first step of that trajectory, and then repeats that process at the next time step. The controller requires a model of the plant and storage, along with a forecast of the future cooling loads.

To apply the optimization approach described in the previous section, models for storage, system power consumption, and building loads are needed. For online optimization, simple empirical models that can be trained using system measurements are appropriate. However, physically based models are best for simulation studies.

The optimization studies that have been performed for ice storage assumed that the state of storage could be represented with a single-state variable. Assuming negligible heat gains from the environment, the relative state of charge (i.e., fraction of the maximum available storage capacity) for any stage k is

$$x_k = x_{k-1} + \frac{u_k \Delta t}{C_s} \tag{63}$$

where C_s is the maximum change in internal energy of the storage tank that can occur during a discharge cycle and u_k is the storage charging rate. The state of charge defined in this manner must be between zero and one.

The charging rate for storage depends on the storage heat exchanger area, secondary fluid flow rate and inlet temperature, and the thickness of ice. At any stage, the maximum charging rate can be expressed as

$$u_{k,max} = \varepsilon_{c,k,max} \dot{m}_{f,max} c_f (t_s - t_{f,i}) \tag{64}$$

where $\varepsilon_{c,k,max}$ is the heat transfer effectiveness for charging at the current state of storage if the secondary fluid flow rate were at its maximum value of $m_{f,max}$, c_f is the secondary fluid specific heat, $t_{f,i}$ is the temperature of secondary fluid inlet to the tank, and t_s is the temperature at which the storage medium melts or freezes (e.g., 32°F).

The minimum charging rate is actually the negative of the maximum discharging rate and can be given by

$$u_{k,min} = \varepsilon_{d,k,max} \dot{m}_{f,max} c_f (t_s - t_{f,i}) \tag{65}$$

where $\varepsilon_{d,k,max}$ is the heat transfer effectiveness for discharging at the current state of storage if the secondary fluid flow rate were at its maximum value of $m_{f,max}$.

In general, the heat transfer effectiveness for charging and discharging at design flow can be correlated as a function of state of charge using manufacturers' data (e.g., Drees and Braun 1995).

A model for the total building power is also needed. At any time

$$P = P_{noncooling} + P_{plant} + P_{dist} \tag{66}$$

where $P_{noncooling}$ is the building electrical use that is not associated with the cooling system (e.g., lights), P_{plant} is the power needed to operate the cooling plant, and P_{dist} is the power associated with the distribution of secondary fluid and air through the cooling coils. The

models used by Henze et al. (1997a) predict cooling plant and distribution system power with a component-based simulation that is appropriate for simulation studies. Alternatively, for online optimization, plant and distribution system power can be represented with empirical correlations. Drees (1994) used curve-fits of plant power consumption in terms of cooling load and ambient wet-bulb temperature. At any time, the cooling requirement for the chiller is the difference between the building load requirement and the storage discharge rate. The chiller supply temperature is then determined from an energy balance on the chiller and used to evaluate the limits on the storage charging and discharging rates in Equations (65) and (66). The chiller cooling rate must be greater than a minimum value for safe operation and less than the chiller capacity. Drees (1994) correlated the maximum cooling capacity as a function of the ambient wet-bulb temperature and the chiller supply temperature. For simulation studies, a building model may be used to estimate building cooling loads. For online optimization, a forecaster would provide estimates of future building cooling loads.

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CHAPTER 42

HVAC COMMISSIONING

COMMISSIONING implements a quality-oriented process for achieving, verifying, and documenting that the performance of facilities, systems, and assemblies meets defined objectives and criteria. The defined objectives and criteria are often referred to as the **owner's project requirements (OPR)**, which involve achieving, verifying, and documenting the performance of each assembly or system to meet the building's operational needs. The commissioning process uses the owner's project requirements as the reference to determine acceptance of the design. Commissioning includes verifying and documenting that the project operational and maintenance documentation and training of operation and maintenance personnel occur. The result should be fully functional systems that can be properly operated and maintained throughout the life of the building.

This chapter gives an overview of the general commissioning process, plus best practices from the July 2004 working draft of ASHRAE *Guideline* 0-2005, The Commissioning Process, developed for the National Institute of Building Sciences' total building commissioning program. Although this chapter provides less detail and is less prescriptive, it provides more narrative discussion on some issues than the cited commissioning guideline draft.

Recommissioning applies commissioning to a project that has been previously delivered using the commissioning process. This may be a scheduled recommissioning developed as part of ongoing commissioning, or it may be triggered by use change, operational problems, or other needs. **Existing building commissioning** (often called **retrocommissioning**) applies commissioning to an existing facility that may or may not have been not previously commissioned. It consists of systematically investigating, analyzing, and adjusting performance of existing building equipment, systems, and assemblies to ensure that required performance (including energy, comfort, and IAQ) is achieved. Buildings require maintenance and tuning to prevent performance degradation. Existing building commissioning should be performed as part of ongoing efforts to maintain a comfortable and efficient environment within the building. It has broad application to virtually every building type and vintage with excellent cost/benefit results and payback ratios.

Applicability

The commissioning process described here applies to new construction, major renovations, and all systems and assemblies. Although this chapter focuses on HVAC commissioning, commissioning can be applied to the building as a total system, which includes structural elements, building envelope, life safety features, electrical systems, communication systems, plumbing, irrigation, controls, and HVAC systems (ASHRAE *Guideline* 0). Which building systems should be commissioned varies with the systems and assemblies used, building size, project type, and objectives. Owners

and commissioning providers often focus on systems and assemblies under the commissioning umbrella that have (1) historically not performed well at turnover (e.g., outside air economizers and variable-speed drives), (2) are mission-critical (e.g., air cleanliness in a cleanroom, emergency power in a hospital), (3) will be costly to fix during occupancy if they fail (e.g., chilled-water piping, window flashing assemblies), or (4) present a life-safety risk if they fail (e.g., fire alarm, smoke control, moisture penetration). Recommendations in this chapter should be appropriately tailored to each project. Although commissioning may begin at any time during the project life cycle, owners obtain the highest benefits when commissioning begins at the conceptual or predesign phase.

Background

Equipment, components, systems, and assemblies have become more complex. More specialization has occurred in the disciplines and trades, with increased interactions between all elements. This increased specialization and interaction requires increased integration between disciplines and specialized systems by the delivery team. Owners often use low-bid policies, and scopes of design professionals are often narrowed. The result has been buildings that do not meet owner expectations and often do not work as intended because of design and construction deficiencies. Commissioning helps overcome these infrastructure inadequacies and fundamentally improve the performance of building systems and living conditions for occupants.

Benefits

The primary benefits of commissioning include improvements in all of the following areas:

- **Predesign and design**
  - Owners develop better understanding of what they want and need through clear, documented OPR
  - Designers understand better what owner is requesting
  - Designers reduce their risk with better communication and input from owner
  - Owners understand better what designers are proposing through a clear, documented basis of design
  - Experts review and improve commissioning documents
- **Construction (including system and assembly performance)**
  - Improved specifications and drawings, resulting in improved coordination between all groups
  - Specifying systems that can be properly commissioned and tested, and are within owner's ability to maintain
  - Tools to help contractors perform better installations (e.g., construction checklists)
  - Performance accountability through construction observation, issue management, and testing
  - Documented verification of system and assembly performance
  - Thorough training requirements in construction documents
  - Verifying training completion

The preparation of this chapter is assigned to TC 7.9, Building Commissioning.

- Formal acceptance testing at completion
- **Occupancy and operations (including maintenance)**
  - Thorough documentation in construction documents
  - Verifying documentation submittals

Commissioning also reduces potential change orders, contractor callbacks, and time required to fine-tune and debug systems during occupancy, and smooths turnover. Building performance improvements give better building and system control, enhance indoor environmental quality, and contribute to increased occupant productivity.

Key Contributors

- Owner
- Engineer/architect
- Commissioning authority (CA)
- Operations and maintenance personnel
- Occupants and users
- Design professionals
- Contractors
- Suppliers

Definitions

Basis of Design (BOD). The basis of design is a document that records how the designer has met the owner's project requirements. It includes the concepts, calculations, system selection decisions, and product selections and how applicable regulatory requirements, standards, and guidelines have been met. The document includes both narrative descriptions and lists of individual items that support the design process.

Commissioning Authority (CA). Retained by the owner, the commissioning authority acts as the owner's advocate, and leads, plans, schedules, and coordinates the commissioning team to implement the commissioning process.

Commissioning Plan. The commissioning plan is a document that outlines the organization, schedule, allocation of resources, and documentation requirements of the commissioning process. This is an overall plan, developed during the predesign, design, and construction phases, that provides the structure, schedule, and coordination planning for commissioning. As construction progresses, the CA updates the plan, which includes details of

- Commissioning scope
- Systems to be commissioned
- Rigor of commissioning
- Team contact information
- Roles and responsibilities of all parties
- Communication and reporting protocols
- Commissioning overview and details of submittal activities
- Construction observation, checklisting, and start-up activities
- Process for dealing with deficiencies
- Test procedure development and execution
- Operation and maintenance (O&M) manual review
- Warranty period activities
- Operation training procedures
- Systems manual development
- Description of summary report, progress and reporting logs, and initial schedule (including phasing, if applicable)

Construction Checklists. Construction checklists are forms used by the contractor to verify that specified systems and components are on site, ready for installation or correctly installed, and functional.

Owner's Project Requirements (OPR). Also referred to as the **design intent**, this document details a project's functional requirements and the expectations of how it will be used and operated. This includes project goals, measurable performance criteria, cost considerations, benchmarks, commissioning, training, documentation, and supporting information.

Systems Manual. The systems manual includes the operation manual, maintenance manual, and additional information of use to the owner during occupancy and operations. This manual expands the scope of traditional operating and maintenance manuals to include other project information such as plans and specifications, approved submittals, operating and optimization procedures, training/commissioning records, and additional information developed and gathered during commissioning.

Test Procedures. This written protocol defines methods, personnel, and expectations for tests conducted on components, equipment, assemblies, systems, and interfaces among systems. Tests clearly describe the test prerequisites, required test conditions, individual systematic test procedures, expected system response and acceptance criteria for each procedure, actual response or findings, and any pertinent discussion. Test procedures differ from **testing requirements** found in the specifications, which describe *what* modes and features are to be tested and verified and under what conditions. Test procedures describe the step-by-step method of *how* to test. Simple checklists may be appropriate for testing simple components, but dynamic testing of interacting components requires more detailed procedures and forms.

COMMISSIONING OBJECTIVE

The commissioning objective focuses on documented confirmation that a facility fulfills the specified performance requirements for the building owner, occupants, and operators. To reach this objective, it is necessary to (1) clearly document the owner's project requirements, including performance and maintainability; and (2) verify and document compliance with these criteria throughout design, construction, acceptance, and initial operation phases.

Specific goals for commissioning include

- Providing documentation and tools to improve quality of deliverables (e.g., forms, tracking software, performance calculation tools)
- Verifying and documenting that systems and assemblies perform according to OPR by end of construction
- Verifying that adequate and accurate system and assembly documentation is provided to owner
- Verifying that operation and maintenance personnel and occupants are properly trained
- Providing a uniform and effective process for delivery of construction projects
- Using quality-based sampling techniques to detect systemic problems
- Verifying proper coordination among systems and assemblies, and among all contractors, subcontractors, vendors, and manufacturers of furnished equipment and assemblies

MANAGEMENT AND RESPONSIBILITIES

Management Strategies

In each project, a qualified party should be designated as the commissioning authority.

Predesign and Design. Commissioning during predesign and design is most often managed by an independent CA who is not part of the formal designer-of-record team. An independent, objective view is critical. The CA normally provides input to the owner and designers but does not have ultimate authority over design decisions. The CA should also coordinate, conduct, or approve activities such as assisting in development of the OPR, conducting statistical sampling reviews, and developing commissioning specifications and test procedures. The CA may also review plan designs. In some projects, commissioning is the designer's responsibility, using either their own staff or a consultant.

Construction. During construction, because of the variety of players, construction management scenarios, and the owner's

objectives, numerous methods are used to manage the commissioning process. To maintain objectivity, the CA should be independent. If the contractor or designer hires the CA, the potential conflict of interest must be carefully managed. The two primary methods to manage commissioning during construction are commissioning-authority-managed and contractor-managed. In the **commissioning-authority-managed approach**, the CA performs many of the planning and technical tasks, like writing the commissioning plan and test procedures and directing, witnessing, and documenting execution of tests, performed by either the contractor or themselves. In the **contractor-managed approach**, the contractor may write the commissioning plan, write test procedures, and direct and document testing, with the CA witnessing selected tests and reviewing completed test reports. The CA should report to the owner on the adequacy of a contractor-managed commissioning plan. The contractor may assign staff, subcontractor, or subconsultant to manage and coordinate commissioning responsibilities. This approach gives the contractor more responsibility. Some view this method as less objective, but others consider it more integrated into the building delivery process than the CA-managed approach.

Some project plans use both management approaches, particularly when a substantial amount of electrical equipment is being tested. HVAC and controls follow the commissioning-authority-managed approach, and electrical system commissioning follows the contractor-managed approach, but the entire process is still overseen by the single CA.

Team Members

Effective building commissioning requires a team effort. The size and makeup of the team depends on the size and complexity of the project and the owner's desire for quality assurance. Team members include the owner, occupants, design professionals, construction manager, general contractor, subcontractors, operation and maintenance (O&M), suppliers, equipment manufacturers, and the CA. All members, particularly the O&M manager, need to be brought into the commissioning process early, preferably during predesign.

The level of effort of team members changes during the different project phases. For example, during design, the designer is a key player in the commissioning process, whereas the contractor may not have been selected. During construction, the general contractor's and installing subcontractors' roles increase.

The scope of work of the CA, design professionals, and contractors should be clearly and completely identified in their contracts. Without this, change orders, incomplete or missed tasks, and otherwise dysfunctional commissioning may result.

Roles and Responsibilities

The commissioning team's responsibilities are to conduct commissioning activities in a logical, sequential, and efficient manner using consistent protocols and forms, centralized documentation, clear and regular communications and consultations with all necessary parties, frequently updated timelines and schedules, and appropriate technical expertise. The following sections summarize the responsibilities of each party. Additional detail is found in the Commissioning Process section.

Commissioning Authority. Specific responsibilities vary with the management scenario and the CA's specific scope of services. Ideally, the same party or firm acts as CA through all project phases. The CA organizes and leads the commissioning team throughout the project.

Design Phase (Including Predesign). During predesign, the CA develops the predesign and design-phase commissioning plan and ensures the OPR is developed.

During design, the CA develops detailed commissioning activities. The core CA responsibilities are

- Reviewing designer's BOD, plans, and specifications, ensuring they meet the OPR
- Developing initial construction-phase commissioning plan
- Ensuring that commissioning, training, and documentation requirements for all contractors and suppliers are reflected in construction contract documents.

Construction and Acceptance. During construction, the CA is in charge of the commissioning process and makes the final recommendations to the owner about functional performance of commissioned building systems and assemblies. The CA directs commissioning activities, possibly performing many of them, depending on the management scenario in place. The CA is an independent and objective advocate for the owner. The core commissioning activities during construction involve

- Reviewing selected construction submittals to ensure conformance with OPR, with updates in commissioning plan as needed
- Observing installations and start-up, including documenting any conditions that require correction
- Organizing, planning, developing, and executing or observing testing
- Developing or assisting with systems manual
- Reviewing O&M manual submissions
- Verifying operator and maintenance personnel training and documentation
- Submitting documented results to owner on all commissioning performed

These tasks may vary (e.g., some commissioning scopes involve preparing the O&M or electronic facility's manuals, preparing detailed maintenance management plans, or conducting operator and maintenance personnel training).

Occupancy and Operations. During occupancy and operations, the CA helps resolve commissioning issues and directs opposite-season testing. Often, the CA participates in a near-warranty-end review of system and assembly performance.

Independence. If the CA's firm has other project responsibilities, a potential conflict of interest exists. Wherever this occurs, the CA should disclose in writing the nature of the conflict and the means by which it will be managed. If the CA is not under direct contract to the owner, the owner's interests need to be protected through appropriate oversight of the CA's work.

Qualifications. The CA should fully understand commissioning, design, and construction processes and have technical design, operations, maintenance, and troubleshooting knowledge of the systems and assemblies being commissioned. Excellent written and verbal communication skills are critical. The CA may represent an individual or a team of commissioning experts, depending on system complexity, the number of disciplines involved, and commissioning scope. Thus, the ability to manage diverse disciplines over long timelines is also important.

Construction Manager. The construction manager's role varies with construction responsibilities. When they have significant oversight for the owner (e.g., schedule management, submittal review, change order authority), their commissioning role is more like the owner's: they ensure the contractor is executing their commissioning responsibilities according to the commissioning plan and help resolve issues.

General Contractors.

Design. The general contractor (if yet selected) reviews commissioning requirements and performance criteria for coordination, schedule, and cost implications.

Construction and Acceptance. The contractor's role and responsibilities are

- Ensuring subcontractors' commissioning work is completed and cooperating with CA in executing the commissioning plan
- Providing input into commissioning plan

- Integrating commissioning schedule into overall project schedule
- Participating in commissioning meetings
- Responding to questions and issues raised by CA
- Resolving issues identified during commissioning and coordinating correction of identified deficiencies
- Providing equipment, system, and assembly data needed by CA
- Performing specified training
- Submitting required portions of systems manuals

In the contractor-managed approach, the general contractor is often required to hire a party with direct commissioning skill to manage and execute the contractor commissioning requirements.

Trade Contractors.

Design. Trade contractors of specialty or complex systems or designs should review commissioning requirements and performance criteria of their systems for coordination, schedule, and cost implications.

Construction and Acceptance. The responsibilities of the installing trade contractors (and vendors, as appropriate) include

- Participating with CA (and the contractor's commissioning manager, when applicable) in executing commissioning plan
- Providing input into commissioning plan
- Coordinating with other trades as necessary to facilitate a smooth and complete commissioning process
- Participating in commissioning meetings
- Responding to questions and issues concerning their work raised by CA
- Executing and documenting tasks in construction checklist and start-up process
- Performing and documenting tests when in their scope
- Participating in resolving issues within their scope identified during commissioning
- Correcting identified deficiencies within their scope
- Providing required documentation for systems manuals and commissioning reports

Commissioning-related activities of trade contractors are to prepare O&M manuals and submissions to the systems manual and provide training on commissioned systems and assemblies. To avoid confusion, the OPR should specify which commissioning activities are the trade contractor's responsibility, and which are the CA's.

Architect and Engineers (Designers).

Design. The design professionals should develop complete basis-of-design (BOD) documentation, including design narratives, rationale, and criteria, according to their scopes of services, and update this document with each new design submission. They provide input to the commissioning plan, respond to questions and concerns by the CA and others, respond to design review comments, and incorporate commissioning requirements in construction contract documents.

Construction and Acceptance. During construction, designers

- Review the commissioning plan
- Attend selected commissioning meetings
- Answer questions about system design and intended operation
- Update design narratives in the BOD to reflect as-built conditions
- Respond to or incorporate CA comments on construction submittals and O&M manuals
- Help resolve design-related issues raised during commissioning
- Perform specified training
- Submit required portions of systems manuals

Additional tasks sometimes required are to present system description overviews for primary systems during O&M staff training, review and approve testing plans and procedures, review completed test forms, or witness selected tests.

Owner's Project Management Staff. The owner's project management staff's ultimate responsibility is to see that the

commissioning plan is executed. The owner should include commissioning responsibilities in all commissioning team members' scopes of services, make sure there is sufficient time for commissioning in the project schedule, ensure the CA is receiving cooperation from other team members, and ensure that other owner responsibilities (e.g., developing the OPR, having O&M staff participate during construction) are fulfilled. The owner ensures that all design review and construction-phase issues identified through commissioning are resolved in a timely manner.

Owner's Representatives. The owner's representatives are individuals or firms hired to represent the owner's interest during specified phases of the building process. The owner typically retains the CA as an owner's representative.

Owner's Operations Staff.

Predesign. The owner's O&M staff should participate in the development of the OPR during predesign.

Design. During design, O&M staff may contribute to reviews of the designer's BOD, plans, and specifications.

Construction and Acceptance. During construction, the owner's O&M staff should

- Assist in reviewing selected submittals
- Assist in construction observation, verifying completion of construction checklists and observing start-up
- Participate in or witness testing, within pre-established lines of responsibility and authority
- Review O&M and systems manual
- Participate in training

COMMISSIONING PROCESS

Commissioning should begin during predesign, and formally continue through the first year of occupancy and operations. Although circumstances may require owners to begin commissioning at the design or construction stage of a project, this later implementation should, when possible, capture the same information and verifications developed when commissioning begins at project inception.

PREDESIGN-PHASE COMMISSIONING

Objectives

The primary activities and objectives of commissioning during predesign are as follows:

- Develop owner's project requirements (OPR)
- Identify scope and budget for commissioning process
- Develop initial commissioning plan
- Accept predesign-phase commissioning process activities
- Review and use lessons learned from previous projects

Activities

Commissioning Team and Management. During the predesign phase, a team is formed to oversee and accomplish commissioning. Responsibility for leadership of the commissioning team should be defined and assigned to the CA at the beginning of predesign.

Owner's Project Requirements (OPR). The OPR forms the basis from which all design, construction, acceptance, and operational decisions are made. It describes the functional requirements of the facility and expectations of how it will be used and operated. It includes project and design goals, budgets, limitations, schedules, owner directives, and supporting information, as well as necessary information for all disciplines to properly plan, design, construct, operate, and maintain systems and assemblies (ASHRAE *Guideline* 0).

The OPR is generally a set of concise objective qualitative statements, each with one or more quantitative performance metrics or criteria. The following information should be included:

- Functional requirements, needs and goals for building use, operation, maintenance, renovation, and expansion, including user requirements
- Occupancy schedules and space plan requirements
- Sustainability, reliability, durability, and aesthetic goals
- Quality of materials and construction
- Warranty, project documentation, and training requirements
- Goals for the process and outcome of design and construction (e.g., budgets, schedules, change orders, safety, aesthetics, effects on adjacent or integral occupied spaces and tenants)
- General commissioning scope and objectives
- General statements about codes and standards to be followed
- Limitations likely to affect design decisions
- Specific features, systems, assemblies, or brands the owner requires (these will be repeated in the design narrative)
- Instructions to designers on types of design tools and aids expected to be used

The CA ensures that the OPR is developed and is clear and complete. The CA may develop or help develop the OPR with the owner or provide direction and review of the OPR developed by others. Facilitated workshops, surveys, and questionnaires are useful for developing the OPR. Later during design, additional OPR statements with performance criteria may be added to the formal list, as desired by the owner and commissioning team. The OPR should still be developed, even if not originally generated in predesign, and included in the systems manual.

Scope and Budget for Commissioning. During predesign, the owner (with the aid of experience from previous similar projects or with the CA) develops a scope and a rough budget for commissioning. At minimum, design-phase activities should be initially scoped. Once a design-phase commissioning plan is developed, the scope and budget may need to be adjusted. The scope and budget should reflect the commissioning objectives in the OPR.

Selecting areas to commission is typically based on the budget, systems or assemblies where the owner has experienced previous problems, complexity of systems and assemblies, and criticality of the system or assembly in meeting the OPR. During predesign and design, the list of areas to be commissioned may be general (e.g., electrical lighting controls, emergency power, general electrical equipment, HVAC, domestic water system, and envelope fenestration). Later in design and before scoping construction-phase commissioning, additional detail should be added to each of these categories, and others added as needed to ensure the scope of commissioning is clear. Adding this detail adds to the cost of commissioning, and needs to be specified early in the design phase.

Historically, commissioning focused on HVAC. Owners are now asking for more systems to be commissioned, including lighting controls, fire and life safety systems, vertical and horizontal transport systems, envelope, plumbing, landscaping, sustainability features, structural elements, many electrical equipment components, security, data, and communications. Refer to the section on Commissioning Costs for budgeting guidelines.

Predesign-Phase Commissioning Plan

One predesign-phase commissioning task should be drafting the commissioning plan for the design phase. The CA develops this plan with review and comment by the owner and designer, and the plan is updated as the project progresses. The design-phase commissioning plan should include the following:

- Objectives and scope
- Overview of the process
- Detailed commissioning process activities for design phase

- General commissioning process activities for construction and operations/occupancy phases
- Roles and responsibilities
- Deliverables
- Communication protocols
- Acceptance and verification procedures
- Schedule
- Checklist of requirements and formats

Acceptance of Predesign Commissioning

The owner's project requirements and commissioning plan should be formally accepted during predesign, after review and comment by the CA.

DESIGN-PHASE COMMISSIONING

Objectives

Design-phase commissioning objectives include the following:

- Update the design-phase commissioning plan developed during predesign
- Update the owner's project requirements (OPR)
- Verify basis of design (BOD) document against OPR
- Verify plans and specifications against BOD and OPR
- Develop commissioning plan for construction and occupancy/operations phases, including draft construction checklist
- Develop and incorporate commissioning requirements into project specifications
- Begin developing systems manual
- Define training requirements for O&M personnel
- Perform commissioning-focused design reviews
- Accept design-phase commissioning

Activities

Update Design-Phase Commissioning Plan. The initial design-phase commissioning plan is developed during predesign. As more becomes known about systems and assemblies likely to be a part of the project and as project objectives are clarified, the commissioning plan may need to be updated with additional detail. The CA must participate in value engineering and constructability review sessions to ensure that commissioning can be performed. The owner and designer then review and comment on the updated plan, which then becomes the guide for the rest of the design phase.

Update the OPR. As design progresses, additional OPR and performance criteria are likely to be identified. Other criteria may need to be altered as more detailed budget and design data become available.

Verify the Basis of Design. All BOD elements can be grouped under one of two terms: design narrative or design rationale. These two terms provide a useful separation when writing the design basis.

The **design narrative** is the written description and discussion of the concepts and features the designers *intend* (during schematic design phase) to incorporate into the design or what they *have* incorporated (during the balance of design) to meet the project requirements and associated performance criteria. This narrative should be understandable by all parties of the building construction and operation process, though it may address fairly technical and specialized issues. The design narrative needs to be updated with each phase of design.

The **design rationale** is the reasoning and underlying assumptions for calculations, decisions, schemes, and system and assemblies selected to meet the OPR and to satisfy applicable regulatory requirements, standards, and guidelines. It includes design assumptions needed to make design calculations and other decisions, such as

- Diversity and safety factors used in sizing

- Classes of systems and components (duct class, cleanroom class, etc.)
- Level of redundancy
- Occupant density
- Limitations and restrictions of systems and assemblies
- Inside and outside conditions (space temperature, relative humidity, lighting power density, glazing fraction, U-value and shading coefficient, wall and ceiling R-values, ventilation and infiltration rates, etc.)
- Summary of primary HVAC load calculations and the methods used

The rationale also gives the reasons for system selection; facility, system and assembly performance assumptions; analytical and design tools used; any limitations and restrictions; operational and use assumptions, including assumptions about level of expertise of operating personnel; guidelines and owner polices; directives; and interpretations of codes.

Development and Use. The BOD is written by the designer and increases in detail as design progresses. The CA may need to obtain this explanatory information from the designer. An updated BOD with increased detail should be submitted with each new design submission. Each submission is reviewed by the owner and CA as part of design reviews.

Develop Commissioning Plan for Construction and Occupancy/Operations Phases. The commissioning plan (CP) includes specifications detailing the scope, objectives, and process of commissioning during the construction and occupancy/operations phases of the project. The CP must specify the scope of work, roles, responsibilities, and requirements of the construction contractor. The commissioning plan for the construction and occupancy/operations phases describes the following:

- Commissioning process
- Scope of commissioning effort, including systems, assemblies, and components being commissioned
- Roles and responsibilities of each team member
- Communication protocols between team members, including documentation requirements
- Procedures for documenting commissioning activities and resolving issues
- Preliminary schedule for commissioning activities
- Detailed procedures for all required tests

The commissioning plan developed during predesign is updated to include construction-phase activities. At the beginning of the design phase, the plan is general and is used primarily to guide development of commissioning specifications. The owner and designer review and comment on the plan. As design progresses, the CA updates and finalizes the plan when the construction documents are completed. The commissioning plan can be issued with the bid documents for reference.

Develop and Incorporate Commissioning Requirements into Project Specifications. The specifications in the CP are needed by contractors so they can include commissioning responsibilities in pricing and understand how to execute the work. Because commissioning is still relatively new to the building industry, descriptive process language should be included, rather than just delineating requirements. Frequently, for reference, the responsibilities of other team members not bound by the specifications (e.g., owner, CA, construction manager, architect) are given in the commissioning specifications to ensure clarity and put the contractor's responsibilities in context.

The specification should include definitions, a list of equipment and systems to be commissioned, submittal, construction checklist, testing and documentation requirements, and sample checklists and test forms. If the project uses contractor-managed commissioning,

the specification should identify skills and qualifications required of the contractor's commissioning lead.

The OPR, along with as much BOD information as possible, should be included in the construction documents and labeled as "Informational Purposes Only" to differentiate from the contractor's contractual obligations. Training and O&M manual requirements of the contractor also should be included.

It is critical that the project specifications in the CP clearly define how the quality control and testing functions that have traditionally been a part of many construction projects (e.g., fire alarm, elevator, duct pressure, emergency power testing) will be integrated with HVAC commissioning. Responsibility for checkout and test procedures, including test procedure review, direction, execution, witnessing, documentation, and approval, must all be clearly described.

The CA ensures that contractor responsibilities for commissioning are appropriately incorporated into the project specifications. Placing the general commissioning requirements, process descriptions, and specifications in a single section ensures that all parties know where to look for their responsibilities and find common terminology.

Often, the commissioning authority writes the commissioning specifications and then works with the designer to integrate them into the project specifications. Alternatively, the designer can develop the commissioning specifications, with the CA reviewing and recommending revisions.

Begin Developing Systems Manual. During design, the systems manual contains the OPR, design basis, and drawings and specifications, updated at each design submission and during and after construction. The CA is often responsible for assembling and maintaining the systems manual; however, the contract documents for the CA or design professionals should delineate who is responsible for assembling the systems manual.

The systems manual differs significantly from traditional O&M manuals. This manual expands the scope to include other project information developed and gathered during commissioning, such as traditional equipment O&M data, design and construction documents (OPR, BOD, plans, specifications, and approved construction submittals), system schematics, final commissioning report, training records, commissioning test procedures (filled-in and blank), and optimization and diagnostic data (which can include operational procedures for specific emergency situations, seasonal changeover procedures, fire and emergency power response matrix, energy efficiency recommendations, troubleshooting guide, recommissioning frequency, and diagnostic building automation system trend logs). Scopes of work should clearly identify whether the systems manual includes all project systems and assemblies or just commissioned ones. For more information, see ASHRAE *Guideline* 4.

The owner, designer, contractor, and commissioning authority each have development responsibilities for parts of the systems manual. Construction documents should list the contents and requirements for the systems manual and the responsible party for generating, compiling, and finishing each part of the required documentation. Systems manuals should be available for and used in operator training. Much of the systems manual can be put into electronic media format. The ability to search and auto-update enhances the usability and accessibility of the data.

Define Training Requirements. During the design phase, the training requirements of O&M personnel and occupants are identified relative to the systems and assemblies to be installed in the facility. O&M personnel must have the knowledge and skills required to operate the facility to meet the OPR. Occupants also need to understand their effect on the use of the facility and the ability to meet project requirements. Both groups require training.

Training needs can be identified using a group technique workshop, interviews, or surveys with the owner and occupant representatives after the systems and assemblies have been specified, and before issuing the construction documents. The contractor's

training responsibilities need to be incorporated into the project specifications and should include requirements for the number of training hours for each item of equipment or assembly and submittals of training plans and qualifications of trainers. Training will likely require participation of the designer (for system overviews), the CA (for system overviews, recommissioning, optimization, diagnostics, and using and maintaining the systems manual), and possibly the contractor, and should be included in their scopes of work. Because turnover in O&M and occupants will occur, training materials should be reusable (e.g., video, written manuals, computer presentations).

Perform Design Reviews. Design review by parties not part of the formal designer-of-record team should be conducted to provide an independent perspective on performance, operations, and maintenance. These document reviews, conducted by experts in the field, should start as early as possible, when options and issues can be more easily resolved. The reviews may be coordinated by the CA and should include the owner's technical staff. The CA may attend some design team meetings, and formally reviews and comments on the design at various stages of development [ideally, at least once during schematic design (predesign), design development, and construction document phases].

A targeted design review may cover the following:

- General quality review of documents, including legibility, consistency, and level of completeness
- Coordination between disciplines
- Specification applicability to project and consistency with drawings
- Verification that BOD assumptions and rationale are reasonable
- Verification that system and assembly narrative descriptions are clear and consistent with OPR and the BOD is updated with resolved issues
- Verification that plans and specifications are consistent with BOD and OPR, and plans and specifications are updated with resolved issues

Potential system performance problems, issues likely to result in change orders, areas where correct installation is difficult, energy efficiency improvements, environmental sustainability, indoor environmental quality issues, operation and maintenance issues, and other issues may be addressed in these design reviews, depending on the owner's desires and CA's scope. Required reviews ensure that training and systems manual requirements are adequately reflected in construction documents.

Some reviews use sampling, giving 10 to 20% of the drawings and specifications an in-depth review; if only minimal issues are identified, the owner accepts the submission. If significant issues are identified in the sample, the submittal is either sent back to the designer for revamping and a thorough review, or the CA may perform a thorough review, depending upon the scope of work defined in the CA's contract. After the design team has addressed the issues, the CA performs a new review. In this type of review, the design team is still responsible for their traditional peer review of construction documents for accuracy. The CA makes recommendations to facilitate commissioning and improve building performance, without approving or disapproving either design or documents. The design team is ultimately responsible for design. The CA should be able to justify all of the recommendations made. It is the responsibility of the owner or project manager to evaluate all review findings with the design team and see that the responsible team member implements the approved ones. All issues are tracked to resolution and verified in later reviews to have been incorporated as agreed.

Accept Design-Phase Commissioning Activities. Commissioning should include the owner's formal acceptance of the BOD, updated OPR, CP, and the design, after review and comment by the CA.

Additional Commissioning Team Tasks. Additional design-phase responsibilities of the commissioning team (led by the CA, who is frequently responsible for these requirements) include the following:

- Build and maintain cohesiveness and cooperation among the project team
- Assist owner in preparing requests for project services that outline commissioning roles and responsibilities developed in the commissioning plan
- Ensure that commissioning activities are clearly stated in all project scopes of work
- Develop scope and budget for project-specific commissioning process activities
- Identify specialists responsible for commissioning specific systems and assemblies
- Conduct and document commissioning team meetings
- Inform all commissioning team members of decisions that result in modifications to the OPR
- Integrate commissioning into the project schedule
- Track and document issues and deviations relating to the OPR and document resolutions
- Write and review commissioning reports

CONSTRUCTION-PHASE COMMISSIONING

Objectives

Commissioning activities should take place throughout the construction phase to include verification and documentation that

- All acceptance testing requirements are documented
- All systems and assemblies are provided and installed as specified
- All systems and assemblies are started and function properly
- The systems manual is updated and provided to facility staff
- Facility staff and occupants receive specified training and orientation
- Acceptance testing occurs

Activities

The following primary commissioning activities (in approximately sequential order) address commissioning objectives. The CA coordinates and ensures that all activities occur successfully.

Bidding and Contract Negotiation. A member of the commissioning team (usually the CA) may attend the prebid conference to present an overview of commissioning requirements and answer questions. Changes that occur during bidding and contract negotiations related to commissioned systems and assemblies are also reviewed to ensure they agree with the OPR.

Commissioning Planning and Kickoff Meetings. The CA coordinates construction-phase planning and kickoff meetings. The planning meeting held with the contractor, owner, designer, and CA focuses on reviewing requirements and establishing specific communication and reporting protocols. The commissioning plan is updated from this meeting. The kickoff meeting is held with additional construction team members, who generally include the mechanical, controls, electrical, and test and balancing contractors. At this meeting, the commissioning provider outlines the roles and responsibilities of each project team member, specifies procedures for documenting activities and resolving issues, and reviews the preliminary construction commissioning plan and schedule. Team members provide comments on the plan and schedule, and the CA uses these suggestions to help finalize the commissioning plan and schedule.

Commissioning Plan Update. The planning and kickoff meetings usually result in an updated commissioning plan. Later, any project phasing or other schedule and scope-related issues (e.g., testing and training plans and schedules) are clarified in further updates.

Submittal Reviews.

Construction Submittals. The CA reviews equipment and material submittals of commissioned systems and assemblies to obtain information needed to develop construction checklists, make meaningful observations of construction progress, and aid in developing comprehensive tests. Submittals are also reviewed to identify construction-related performance issues before construction progress makes them more difficult and expensive to address. Submittals should be reviewed concurrently by the design team to allow any discrepancies to be identified and communicated to the design team before formal approval.

Controls Submittal and Integration Meeting. Before the contractor develops the controls submittal, the CA coordinates a controls integration meeting to discuss and resolve methods for implementing performance specifications or strategies, interlocks between systems, priority of control between packaged controls and the central control system, the control system database, point names, graphic details and layout, access levels, etc.

Coordination Drawings. The CA may help the owner monitor the development of coordination and shop drawings to ensure synchronization between trades.

Early O&M Data. Information beyond typical construction submittals requested by the CA includes installation and start-up procedures, operation and maintenance information, equipment performance data, and control drawings before formal O&M manual submittals. This information allows the CA to become familiar with systems and assemblies to develop construction checklists, start-up plans, and test procedures.

Contract Modifications Review. Construction documentation issued during this phase, including requests for information, construction field directives, and change orders, should be reviewed by the CA to identify issues that may affect commissioning and compliance with construction documents, BOD, or OPR.

Schedule Commissioning Field Activities. The CA works with the contractors and construction manager to coordinate the commissioning schedule and ensure that commissioning activities are integrated into the master construction schedule.

Construction and Commissioning Meetings. The CA attends periodic planning and job-site meetings to stay informed on construction progress and to update parties involved in commissioning. During initial construction, the CA may attend regular construction meetings and hold a line item on the agenda. Later, the CA may convene entire meetings devoted to commissioning issues, with more frequent meetings as construction progresses. Attendees vary with the purpose of the meeting. Team members should be represented at meetings by parties with technical expertise who are authorized to make commitments and decisions for their respective organizations. The CA should distribute minutes from these meetings.

Progress Reports. The CA provides periodic progress reports to the owner and contractor with increasing frequency as construction progresses. These reports indicate current progress, next steps, and critical issues affecting progress and construction schedule.

Update Owner's Project Requirement and Basis of Design. When contract negotiations and/or changes and clarifications made during construction alter or add to the OPR or BOD, these documents should be updated. Normally, the CA updates the OPR and the designer the BOD. Final construction updates to these documents are made at the end of testing, typically a few months into occupancy.

Coordinate Owner's Representatives Participation. The commissioning plan should describe participation of the owner's representatives in work such as submittal review, construction checklist verification, construction observation, test procedure review and execution, and O&M manual review. The CA normally coordinates this participation with the contractor.

Construction Observation. The CA should make planned, systematic visits to the site to observe installation of systems and assemblies. The owner's staff may assist in construction observation. The CA should verify that the first few of any large-quantity items (e.g., variable-air-volume terminal units) are installed properly and used as a mock-up or standard to judge the rest of the installation. Any conditions not in compliance with the construction documents or BOD or that may affect system performance, commissioning, operation, or other project requirements should be documented. These observations normally focus on areas where observers have found problems before, or spot-check items on construction checklists. Less often, practitioners are tasked with validations or detailed inspections verifying that equipment or assemblies have been installed properly in every detail. Some practitioners make formal construction observation reports, whereas others merge findings into the regular issue logs and progress reports. Site visits should be used to verify completion of construction checklists.

The CA normally witnesses many of the contractor's start-up activities for major equipment to ensure checklists and start-up are documented properly and to gain additional feature and function information from installing technicians.

Construction Checklists and Start-up. At the beginning of construction, construction checklists are developed (usually by the CA, but sometimes by the contractor or equipment manufacturer) for most commissioned systems and equipment. They are attached to or integrated with manufacturer's installation and start-up procedures. In most projects, contractors fill out the checklists during installation, start-up, and normal checkout of equipment and systems, though some commissioning practitioners fill out the checklists themselves. The contractor fully documents start-up and initial checkout, including the construction checklists, and submits them to the CA, who reviews the forms and spot-checks selected items in the field later in the project, to ensure systems are ready for testing.

Some CA practitioners statistically sample items on checklists to verify proper completion (typically random or targeted sampling 2 to 20%). If an inordinate fraction of the sampled items are deficient (typically more than 10%), the contractor is required to check and document all remaining items. The contractual documents need to contain details of the sampling and actions based on the results.

Commissioning Issues Management. The CA keeps a record of all commissioning issues that require action by the design team, contractor, or owner. The issues should remain uniquely identified, be tied to equipment and systems, and prioritized relative to performance, cost, and schedule. Issues are tracked to resolution and completely documented. The CA distributes the updated log to the owner, contractor, and construction manager at construction and commissioning meetings. This log can also be placed on project Web sites. In the contractor-managed scenario, the contractor's commissioning manager or subconsultant may manage the contractor's issues log. In that case, to minimize conflicts of interest, the commissioning authority is often required to report all issues simultaneously to the contractor and to the owner.

Developing Test Procedures. Step-by-step test procedures and project-specific documentation formats are used for all commissioned equipment and assemblies. **Manual tests** evaluate systems with immediate results. **Monitoring testing** uses the building automation system or data loggers to record system parameters over time and analyze the data days or weeks later. **Automated testing** gathers or analyzes system performance data completely electronically, or with significant help from software.

Test procedure writing begins immediately after the submittal, because test procedures need to be reviewed and approved before testing occurs, which is generally scheduled about three to six weeks after the submittal review. Test procedures may be based on specifications, applicable standards and codes, submittal data, O&M data, data shipped with the equipment, approved control drawings, and existing test procedures of similar equipment or components. Tests should cover all functions and modes.

The CA is responsible for verifying that the test procedures are written and appropriate for determining that equipment, assemblies, and systems function correctly. Test procedures are written by the equipment manufacturer, contractor, engineer, CA, or a combination thereof, depending on their scopes of work. All parties should have input into the final test procedures to ensure that equipment, assemblies, systems, or people will not be endangered or warranties voided. Industry standard test procedures [e.g., ASHRAE, Air-Conditioning and Refrigeration Institute (ARI), American Composites Manufacturers Association (ACMA)] should be referenced whenever possible.

Testing and Verification.

Responsibilities and Management. Not all testing and verification falls under HVAC commissioning. Traditional air and water testing, adjusting, and balancing is often the sole responsibility of the contractor or by independent contract to the owner. Building envelope, elevators, and electrical system testing are also generally excluded from HVAC commissioning. There is some movement in the industry to centralize coordination for quality assurance/quality control (QA/QC) functions under the commissioning team. Each project is unique, and different approaches can be warranted.

Critical issues include ensuring that

- Appropriate testing rigor is applied
- Technically qualified parties execute and document the testing
- Objectivity is maintained
- Testing is well documented

For systems not usually thoroughly tested by the contractor [e.g., HVAC systems and controls, lighting controls, specialty plumbing, and envelope and interfaces between systems (security, communications, controls, HVAC, emergency power)], the CA may write test procedures that go beyond HVAC tests. The CA then directs, witnesses, and documents each test executed by the contractor. For these systems, the controls subcontractor usually executes the tests, although the CA may test some equipment with or without the contractor present.

Testing that has traditionally been conducted by the contractor (e.g., fire alarm, fire protection, elevator, duct and pipe tests, emergency power, some electrical equipment) ideally should be centrally coordinated. This can be the responsibility of the contractor or of the CA. The specifications should clearly establish testing and documentation requirements and define the responsible party. The level of confidence and objectivity can be increased by requiring experts in specific disciplines to witness tests, particularly in some electrical system and envelope assembly field testing. Increasing the required amount of field witnessing by the CA also improves the confidence that commissioning was correctly performed.

Within a given discipline, there may be differing levels of autonomy. For example, in tests of electrical equipment (e.g., circuit breakers), the contractor may conduct and document the bolt torque tests, and also be required to hire an independent certified testing agency to conduct other necessary tests that require more specialized expertise and test equipment.

The owner's technical staff can assist in and benefit from participation in any of the above scenarios. The designer and owner's project management staff may witness selected tests.

Verification Testing Scheduling. Verification testing should be performed after equipment and assemblies are complete, started up, and checked out; construction checklists submitted; and air and water balancing complete. The contractor is then ready to turn the system over to the owner. Some practitioners require a certificate of readiness from the contractor certifying that the system has been thoroughly checked out and verified to be completely functional. Ideally, manual testing occurs before substantial completion, but schedule slippage may require testing to occur after this milestone. Some short-term monitoring may be completed with manual testing, but most is postponed until early occupancy. Opposite-season and other deferred testing should be conducted during seasonal changes or peak seasonal conditions.

Testing Scope. At a minimum, testing includes observing and documenting system operation and function during normal operation, through each of their sequences of operation, and all other modes of operation and conditions, including manual, bypass, emergency, standby, high and low load, and seasonal extremes, and comparing actual performance to that specified in the construction documents. Testing may also be conducted to verify performance criteria found in the BOD and OPR, including system optimization, though deficiencies in these areas are not normally the contractor's responsibility.

Manual Testing Methods. Testing includes observing normal operation; changing set points, schedules, and timers; and exercising power disconnects, speed controls, overwriting sensor values, etc., to cause perturbations in the system. System response and results are recorded on test procedure forms, and any issues are documented. Small corrections are often made during testing. Less pressing corrections or issues with unknown solutions are investigated later, corrected, and retested.

Building automation systems (BAS), when present, can be the backbone for conducting much of the testing, collecting, and archiving data. Before using the BAS, critical sensors, actuators, and features should be verified as calibrated so the system readouts are reliable (although all sensors and actuators should have been calibrated by the contractor and documented on construction checklists). The results are viewed on the building automation system screen or at the equipment. Other tests may require handheld instruments or visual verification (e.g., evaluating caulking and flashings on window installations).

Monitoring. Some testing requires monitoring (trending) system operation over time through the BAS or data loggers (when the BAS does not monitor desired points). Monitoring can be used to document that systems are performing properly during test conditions over the monitoring period. However, this is not a substitute for manual testing, which can cover a wide range of conditions. Monitoring provides a view of system interactions over the course of normal, start-up, shutdown, and weekend operation. Normally, the CA analyzes monitored data and submits a report, with any concerns added to the issues log.

Automated Testing. Various semiautomated testing is conducted in permanent onboard equipment controllers. Currently, most truly automated testing focuses on identifying electrical faults in controller components and is used during vendor start-up and troubleshooting activities. Some use logic to identify parameters outside limits, which indicate component malfunctions such as hunting and calibration issues. Different types of automated testing intended to help commissioning are under development. Some are primarily tools to gather and display monitored data; others help the analyzer make diagnoses. Equipment manufacturers often integrate automated commissioning testing capabilities into onboard controllers on their equipment.

Training. Training should include, as appropriate, (1) the general purpose of the system; (2) use and management of the systems manual; (3) review of control drawings and schematics; (4) start-up, shutdown, seasonal changeover, and normal, unoccupied, and manual operation; (5) controls set-up and programming; (6) diagnostics, troubleshooting, and alarms; (7) interactions with other systems; (8) adjustments and optimizing methods for energy conservation; (9) relevant health and safety issues; (10) special maintenance and replacement sources; (11) tenant interaction issues; and (12) discussion of why specific features are environmentally sustainable. Occupants may also need orientation on certain systems, assemblies, and features in the building, particularly sustainable design features that can be easily circumvented.

The CA helps the owner ensure that adequate training plans are used by the contractor and that training is completed according to the construction documents. (See the discussion of defining training

requirements in the section on Commissioning During Design.) Some CAs conduct testing with a sample of trainees to verify the efficacy of the training.

Most training should be accomplished during construction, before substantial completion. However, for complex systems (e.g., control systems), multiple training sessions should occur before and after substantial completion. Training for systems that will not come into operation until the next season may be delayed. A meaningful training program typically includes using the operation and maintenance components of the systems manual, which must be submitted before training begins. Selected training materials can be video-recorded as desired by the owner.

Commissioning Record. The CA compiles all commissioning documentation and project data, which are submitted and become part of the systems manual. The commissioning record contains the salient documentation of commissioning, including the commissioning final report, issues log, commissioning plan, progress reports, submittal and O&M manual reviews, training record, test schedules, construction checklists, start-up reports, tests, and trend log analysis, grouped by equipment.

Final Commissioning Report. The CA should write (or review) and submit a final commissioning report detailing, for each piece of commissioned equipment or assembly, the adequacy of equipment or assemblies meeting contract documents. The following areas should be covered: (1) installation, including procedures used for testing equipment with respect to specifications; (2) functional performance and efficiency, including test results; (3) O&M manual documentation; and (4) operator training. Noncompliance items should be specifically listed. A brief description of the verification method used (manual testing, trend logs, data loggers, etc.) and observations and conclusions from the testing should be included. The CA updates the final commissioning report after occupancy/ operations-phase commissioning.

Systems Manual Submittal. The CA usually compiles the systems manual and provides it to the owner. At the end of construction, the designer, contractor, owner, and CA provide elements of the systems manual generated during the construction phase. The systems manual should include commissioning test procedures, results of commissioning tests, issue logs and resolution, system schematics, O&M information, record drawings, construction checklists, start-up reports, and trend log analysis, grouped by equipment. The CA normally reviews and approves systems manual submissions by the contractor and designer, similar to traditional O&M manual reviews. Electronic systems manuals, now developed occasionally, will likely become standard in the future.

OCCUPANCY- AND OPERATIONS-PHASE COMMISSIONING

Occupancy- and operations-phase commissioning typically begins with resolving the findings from performance monitoring over the first month or two into occupancy, and ends with the completion of the first year of occupancy.

Objectives

Commissioning during this phase should ensure the following:

- Initial maintenance and operator training is complete.
- Systems and assemblies received functional opposite-season verification.
- Outstanding performance issues are identified and resolved before warranty expiration.
- Commissioning process evaluation conducted and satisfactorily resolved.

Activities

Verifying Initial Training Completion. The CA ensures that any remaining training is conducted according to the contract documents, either by reviewing documentation of the training or through witnessing portions of the training. This normally applies to control systems and training on major systems for which peak season is not near the end of the construction phase.

Opposite-Season Testing. Opposite-season testing verifies proper operation of those systems for which peak load conditions are not available before substantial completion. For example, when completion occurs in winter, final full-load cooling system testing must wait until the following summer. Testing should be performed by the appropriate contractor and witnessed by the CA and building operators. However, the owner's operations staff and the CA, if sufficiently proficient with the controls system, can execute the tests and recall contractors only if there are problems.

Near-Warranty-End Review. The CA may also be asked to return a few months before the contractor's one-year warranty expires, to interview facility staff and review system operation. By acting as the owner's technical representative, the CA assists facility staff address any problems or warranty issues.

Documentation Update. Any identified operations-phase concerns are added to the issues log and the final commissioning report is amended to include occupancy/operations-phase commissioning activities. Changes to the BOD, OPR, or record documents are documented by updating the systems manual near the end of the warranty. Changes to sequences of operation require particular care in ensuring that these updates occur.

Commissioning Process Evaluation. The CA should meet briefly with the owner; general, controls, mechanical, and electrical contractors; and mechanical and electrical designers to discuss the commissioning process for this project. Topics to be addressed include what went well, what could be improved, what would best be done differently next time, etc. This will benefit all parties in commissioning future projects. The CA will submit a report on this meeting to the owner.

The occupancy/operations phase typically begins with resolving the findings from monitoring a month or two into occupancy, and ends when the one-year equipment warranties expire.

Additional Activities. The CA may also be given other responsibilities during the warranty period, such as helping develop a maintenance management program, optimizing system performance, and developing electronic facility manuals.

Ongoing or Recommissioning. Ongoing monitoring and periodic retesting and calibration of selected systems and assemblies is recommended to ensure they comply with the OPR, operating and functioning optimally throughout their life. This is sometimes called recommissioning. Some recommissioning methods rely more on semicontinuous monitoring of primary system performance parameters with periodic analysis. Other approaches consist of recalibrating and retesting targeted systems and components on a regular schedule, including both manual testing and monitoring. Calibration and test frequency vary with equipment and its application.

COMMISSIONING COSTS

Commissioning costs vary considerably with project size and building type, equipment type, scope, and traveling requirements (Mills 2004; Wilkenson 2000). Historically, commissioning focused on HVAC and controls, and started during construction. However, QA/QC for increasing numbers of systems is being included in commissioning, and the process now frequently begins in the design phase. Currently, the commissioning industry is not mature; budget estimates, even for relatively detailed scopes of work, vary widely.

Clear definition of tasks, deliverables, systems and components to be commissioned, rigor, and testing methods must be provided for comparative pricing. The costing guidelines that follow must be used with great caution and are provided only for rough planning purposes. Understanding what is and what is not included in each cost number is critical. *Owners should consult commissioning*

providers with their planned projects to obtain budget estimates, and practitioners should use detailed cost breakdowns for their pricing.

DESIGN-PHASE COSTS
(INCLUDING PREDESIGN AND DESIGN)

Predesign-phase costs include the CA's efforts in attending predesign meetings and design reviews with the architect's consulting team and owner's representatives. This portion of work may range from 8 to 12% of the CA's contract. Design-phase costs include the CA's reviewing design submittals, coordinated with the designer, and developing sections of the systems manual (design intent and basic operations from the control submittal). This portion of the work may range from 15 to 20% of the CA contract.

For a project that includes the discussed tasks for all HVAC and controls components, a moderate level of electrical systems commissioning, and minor plumbing and envelope commissioning, the total commissioning costs (CA cost plus the additional work of the designers) may range from 0.2 to 0.6% of the total construction cost for a typical office building. This estimate assumes two moderate design reviews. Different types of buildings or more complex buildings with larger scopes of design review may cost considerably more.

CONSTRUCTION- AND OCCUPANCY/
OPERATIONS-PHASE COSTS

Table 1 estimates the CA's costs for the construction and occupancy/operation phases under the CA-managed approach. It includes construction- and occupancy/operations-phase commissioning for the HVAC system (including fire, life, safety and controls) and electrical system (including lighting controls, emergency power, and limited connection and grounding checks). It does not include specialty testing such as full infrared scanning, power quality, switch gear, transformer, or low-voltage-system testing. Complex systems and critical applications have higher costs. *For a given building type and complexity*, larger buildings tend to come in at the lower end of the range and smaller buildings at the higher.

The listed costs cover only the CA fees; there are also costs to the contractor, designers, and owner's staff. For the CA-managed approach, costs for the mechanical contractor attending meetings, documenting construction checklists, and assisting with testing will approximate 10 to 20% of the CA's mechanical commissioning costs. The electrical contractor's costs may equal the CA's electrical commissioning costs for electrical commissioning (because contractors are usually responsible for hiring their own electrical testing company to perform electrical tests). International Electrical Testing Association (NETA) tests are often already part of the normal construction program, and the only additional commissioning costs are for the CA to coordinate testing, spot-witness, and review reports.

Commissioning costs for the contractor-managed approach are similar overall, but more costs are shifted from the CA to the contractor and their commissioning manager and staff.

EXISTING BUILDINGS

Existing building commissioning (also called retrocommissioning) involves commissioning building HVAC equipment after the

Table 1   Estimated Commissioning Authority Costs to Owner for Construction and Occupancy/Operations Phases

Commissioned System	Total Commissioning Cost
HVAC and controls[a]	2.0 to 3.0% of mechanical
Electrical system[a]	1.0 to 2.0% of electrical
HVAC, controls, and light electrical[b]	0.5 to 1.5% of construction

Sources:
[a]Wilkinson (2000).
[b]PECI (2000).

equipment has been installed, and the facility is running and occupied. HVAC equipment performance normally degrades with use and time, at a rate depending on the quality of maintenance and operations. Quality of maintenance also affects equipment life expectancy. A facility retrocommissioning effort should include developing an owner's project requirements or owner's intent, documentation of the existing system, a survey identifying operational inefficiencies for the facility, quantifying and prioritizing the inefficiencies found, determining how to best optimize the equipment or operation, implementing the change, and then reverifying with ongoing measurements that the retrocommissioning activities produced and continue to produce the desired effect (Claridge et al. 2000). Other definitions specify it as a one-time event with a different set of project phases (Haasl and Sharp 1999; Thorne and Nadel 2003). All of these approaches provide methodologies to improve operation and lower a facility's energy use with direct consideration given to the current operational requirements.

Existing building commissioning activities include reviewing utility bills and building documents, optimizing chiller and boiler systems, implementing various equipment operational scheduling, optimizing air delivery systems, setting up temperature resets for the water- and air-side operations, optimizing indoor air quality control, and verifying control systems are functioning as needed. When existing systems may not have the capacity to meet the owner's project requirements, system deficiencies need to be documented with a decision on when (or whether) upgrading will be done. For example, indoor air quality objectives may not be met because a system was designed under an older standard or code. Temperature objectives may not be met because additional computer equipment loads have been added to some spaces, and the original system was designed to handle a lower load. In each case, a documented recommendation should be provided to the owner on the options available.

RCx has been shown to be a very cost-effective way to improve occupant comfort and lower costs. Energy savings of over 20% with a two-year payback have been reported (Claridge 2004). Also, Kats et al. (1999) showed that RCx typically achieved 40% or more savings than was estimated during a range of audits.

Buildings with systems ranging from older pneumatic controls to newer energy management and control systems (EMCSs) have been successfully retrocommissioned. Pneumatic controls limit the number of RCx options that can be implemented, and also require separate data logging for monitoring parameters used to calculate energy savings. Modern EMCSs enable lower-cost RCx and also allow trend logging of various parameters to sustain the achieved savings.

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CHAPTER 43

BUILDING ENVELOPES

BUILDINGS are designed and constructed to provide shelter from the weather and typically to provide conditioned space for the intended occupancy, whether it be residential, office, medical, museum, manufacturing, etc. During design, fundamental decisions are made about the foundation, walls, roof, selection of windows and doors, and the HVAC system.

The **building envelope** consists of those parts of the building that separate the controlled indoor environment from the uncontrolled outdoor environment. It typically includes the **foundation**, **floors**, **walls**, **fenestration** (windows and doors), and **roof**. To make good decisions, the designer must take into account design climate factors such as winter temperature, summer temperature and relative humidity, wind speed, peak and annual rainfall, and seismic zone.

The building envelope should (Hutcheon 1963)

- Control
  - Heat flow
  - Airflow
  - Water vapor flow
  - Rain penetration
  - Light, solar, and other radiation
  - Noise
  - Fire
- Provide strength and rigidity
- Be durable
- Be aesthetically pleasing
- Be economical

Although the overall design of the building envelope is normally the project architect's responsibility, many of these performance requirements are addressed by consulting engineers. Control of heat, airflow, and moisture arise from the building envelope's function of separating the controlled indoor environment from the uncontrolled outdoor environment. As a consequence, the HVAC designer should be knowledgeable about the interdependency between the building envelope and HVAC system; review the envelope's heat, air, and moisture control characteristics; and provide knowledgeable input to the design team if the functional program for the building environment is incompatible with the performance of the building envelope as designed.

This chapter applies information from Chapters 23 to 25 of the 2005 *ASHRAE Handbook—Fundamentals* to building envelope design. It separately addresses single-family residential buildings, which are usually designed using a prescriptive approach, and institutional, commercial, and industrial buildings, which are designed by a team consisting of the owner, architect, and consulting engineers.

The preparation of this chapter is assigned to TC 4.4, Building Materials and Building Envelope Performance.

SINGLE-FAMILY RESIDENCES

Foundations and Floors

Foundation design for single-family residences entails not only structural soundness, but also appropriate energy, moisture, termite, and radon control. In North America, several building energy codes recommend foundation insulation in climates with more than 2500 heating degree-days (base 65°F). An uninsulated, conditioned basement may lose up to 20% of the heat in a tightly sealed house that is well insulated above grade.

Although saving energy is an important incentive, insulating basement foundations also creates a more comfortable, livable space at a relatively low cost. Raising basement temperatures in cold climates reduces condensation, minimizes problems with mold and mildew, and helps maintain acceptable indoor air quality.

Construction. The three basic types of foundations are basement, crawlspace, and slab-on-grade. Each requires specific attention to details of environmental separation. The cost of higher insulation levels can be compared with the savings in several ways, but a life-cycle cost analysis is the best method (Carmody et al. 1991). It takes into account a number of economic variables, including installation costs, mortgage rates, HVAC efficiencies, and energy costs.

Conditioned Basements. A concrete or masonry basement wall may be insulated by (1) insulating the exterior upper half, (2) insulating the entire exterior wall, or (3) insulating the entire interior wall.

Crawlspaces. A crawlspace can be designed as a short basement (with a floor). Because the floor is above grade, it is less subject to moisture hazards than a slab floor. However, if moisture problems occur, they are more likely to be noticed in a basement because it is more accessible than a crawlspace. Although most codes require operable louvered vents (1 ft^2 per 1500 ft^2) near each corner of a crawlspace, research has shown that moisture-retardant ground cover is more effective and, in most locations, eliminates the need for vents (ASHRAE 1994).

In an unconditioned crawlspace, insulation is placed between the floor joists. In an unvented crawlspace, either the concrete or masonry walls or the floor above can be insulated. If the walls are insulated, air infiltration paths such as the interface between the crawlspace wall and bottom plate of the floor above must be sealed. Intersections of two hard surfaces are common air infiltration paths. Walls may be insulated on the (1) entire exterior wall, (2) entire interior wall, or (3) entire interior wall and perimeter of the crawlspace floor to a depth of 2 ft. When the floor is insulated, appropriate ground cover must be installed to control moisture in the crawlspace and to prevent high moisture levels from degrading the thermal performance of the insulation. In pressure-treated wood construction, insulation is placed in the cavities between the wood studs.

The disadvantages of a vented crawlspace are that (1) pipes and ducts must be insulated; (2) a larger area must be insulated (the floor area is greater than the wall area), which may increase the cost; and (3) in some climates, warm, humid air circulating in the crawlspace can cause the wood to have an excessive moisture content. However,

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vented crawlspaces are often provided with operable vents that can be closed to reduce winter heat losses (closing them may, however, increase radon levels). Also, these vents can be closed in summer to keep out moist exterior air that may have a dew point above the crawlspace temperature. However, unless steps are taken to control air infiltration, closing vents does not ensure that the crawlspace has no air exchange with the outside; any exchange with outside air reduces thermal performance.

There are several advantages to designing crawlspaces as unvented, semiconditioned zones. Duct and pipe insulation can be reduced, and insulating the foundation at the perimeter instead of the floor above requires less insulation, simplifies installation, and minimizes condensation. Although increased airflow by venting can dilute ground-source moisture and radon, complementing control measures such as ground covers and proper drainage, it will not eliminate them. Venting crawlspaces may be desirable in areas of high radon hazard, but it should not be considered a reliable radon mitigation strategy. Depressurizing the crawlspace is effective at minimizing soil gas uptake. In flood-prone areas, vents may serve the additional function of hydrostatic equalization across the foundation, and unvented crawlspaces may be impractical to construct.

Slab-on-Grade. For slab-on-grade foundations with concrete or masonry walls, insulation is usually placed on the entire exterior surface of the foundation stem wall, on the interior surface of the foundation wall, or horizontally under the slab perimeter. When the insulation is placed on the interior, it is important to place it in the joint between the slab edge and the foundation wall.

Another method is to place insulation horizontally on the building exterior extending 2 to 4 ft into the surrounding soil. Shallow footings (less than 2 ft below grade) or slabs with a thickened edge and no foundation wall are common in some regions. In these cases, additional insulation may be placed horizontally along the exterior edge.

Thermal Performance. A key question in foundation design is whether to place insulation inside or outside the basement or crawlspace wall. Placing rigid insulation on the **exterior** of a concrete or masonry basement or crawlspace wall has some advantages: it provides continuity without thermal bridges, keeps the waterproofing and structural wall at moderate temperatures, minimizes moisture condensation problems, does not reduce interior basement floor area, and includes the foundation in the building thermal mass. Exterior insulation at the rim joist leaves joists and sills open for inspection from the interior for termites and decay.

However, exterior insulation can provide a path for termites and can prevent inspection of the wall from the outside. A termite shield may need to be installed through the insulation where the sill plate rests on the foundation wall. Vertical, exterior insulation can extend as deep as the top of the footing and can be supplemented by extending insulation horizontally from the face of the foundation wall.

Interior insulation is an effective alternative, and it is generally less expensive if the costs of interior finish materials, including a flame spread cover, are not included. However, interior wall insulation increases the exposure of the wall to thermal stress and freezing and may increase the likelihood of condensation on sill plates, band joists, and joist ends.

In a wood foundation, insulation is placed between studs. Insulation placed around the crawlspace floor perimeter can provide additional thermal protection; however, it may also create additional paths for termite entry. A 2 in. air space between the lower end of the insulation in a crawlspace or wall cavity and the bottom plate of the foundation wall allows inspection for insect infestation. Batt or tight-fitting rigid foam board insulation is commonly placed inside the rim joist.

In a foundation system of wood pressure-treated with preservative, insulation is placed in the stud cavities as for above-grade insulation in a wood frame wall. Crawlspace walls may also be insulated by spraying insulating foam.

Insulation may also be incorporated in concrete or masonry walls. Examples include rigid foam plastic insulation cast within the concrete wall; formed interlocking rigid foam units that serve as a permanent, insulating form for cast-in-place concrete; and masonry blocks made with polystyrene beads or a low-density aggregate/regular-density concrete mixture. However, the effectiveness of construction that insulates only a portion of the wall area should be evaluated closely because thermal bridges can significantly reduce the insulation's effectiveness.

For **slab-on-grade systems**, the greatest heat loss is through the small area of the foundation wall above grade. Heat is also lost from the slab to the soil. Heat losses to the soil are greatest at the slab edge and diminish rapidly with depth. Slab heat loss both at the edge and through the soil must be considered in designing the insulation system.

Insulation can be placed vertically outside the foundation wall or grade beam. This approach effectively insulates the exposed slab edge above grade and extends downward to reduce heat flow from the floor slab to the ground surface outside the building.

Vertical exterior insulation is the only method of reducing heat loss at the edge of an integral grade beam and slab foundation. A major advantage is that the interior joint between the slab and foundation wall need not be insulated, thus simplifying construction. However, there are several drawbacks to this method. The rigid insulation must be covered above grade with a protective board, coating, or flashing material; brick facings that contact the covering can create a thermal short that bypasses both the foundation and above-grade insulation. A further limitation is that the depth of the exterior insulation is controlled by the footing depth. Vertical exterior insulation may provide concealed pathways for termite infestation in some climate areas.

Thermal insulation also can be placed vertically on the interior of the foundation wall or horizontally under the slab. In both cases, heat loss is reduced and the difficulty of placing and protecting exterior insulation is avoided. Interior vertical insulation is limited to the depth of the footing, but underslab insulation is not. Usually, the outer 2 to 4 ft of the slab perimeter is insulated. The joint between the slab and the foundation wall must contain insulation whenever insulation is placed inside the foundation wall or under the slab. Otherwise, a significant amount of heat transfers through the thermal bridge at the slab edge. Insulation is generally limited to a thickness of 1 in. at this point.

Another option for insulating a slab-on-grade foundation is to place insulation above the floor slab. A wood floor deck can be placed on sleepers, leaving cavities that can be filled with rigid board or batt insulation, or directly on rigid insulation above the slab, which avoids some construction detail problems inherent in more conventional approaches, but may cause a greater frost depth near the slab edge.

Moisture Control. High moisture levels in a foundation can rapidly degrade the thermal performance of most types of foundation insulation. Properly constructed foundations with good drainage and damp-proofing should keep moisture loads from foundations below 0.8 gal/day; however, Christian (1994) reported foundations that contribute 0.5 to 20 gal/day. Elevated moisture levels increase the potential for mold and mildew growth, odors, pathogens, and serious health effects to occupants. Because the surface temperature is colder during winter than the crawlspace air, the relative humidity of the crawlspace air can be much lower than on the surface. Frequently, methods used to solve the problem in existing buildings are energy-intensive (e.g., year-round operation of dehumidifiers). In warm, humid climates, the dew-point temperature of crawlspace air is often high. This results in surface relative humidity above the 80% threshold identified by Hens (1999) at which fungal defacement is likely to develop.

Basement. Rain is carried away by gutters, downspouts, grading away from the building, and a cap of low-permeability backfill

material. Subgrade drainage by a drain screen (gravel and footer drain connected to daylight, sump, or storm sewer) prevents water from reaching the foundation wall.

Damp-proof or waterproof materials on the exterior of the foundation wall and over the top of the footing control moisture transport. Capillary moisture movement into the slab is controlled by a 4 in. thick granular layer under the slab.

All air leakage openings (e.g., floor slab/wall intersection, rim joist area) are sealed with durable caulking materials, closed with gasket systems, taped, or covered with membranes. Material selections should be based on the climate in which the structure is located.

Damp-proofing on the wall and polyethylene under the slab control vapor diffusion. During heating periods, vapor diffusion from the basement interior may transport moisture into the rim joist framing, where it accumulates. Rigid insulation installed on the exterior of the rim joist limits periods of potential condensation.

Slab-on-Grade. The ground should be graded to direct water away from the building; many codes recommend a 5% grade extending 10 ft from the foundation. A granular layer under the concrete slab provides a capillary break between the soil and slab. This layer can also be integrated into a subslab ventilation system to reduce radon levels. Extending the vapor retarder over the top of the foundation wall and placing appropriate flashing for any brick facing provide a capillary break to protect the above-grade wall from ground moisture penetration.

A vapor retarder placed under the slab restricts both radon gas entry and water vapor diffusion through the slab. If ducts are placed in the slab, moisture may enter the conditioned space because groundwater and soil gas will likely seep into the ducts.

Air Movement/Radon Control. Construction techniques to minimize radon infiltration through the foundation are appropriate where radon is present. General approaches include sealing joints, cracks, and penetrations in the slab and walls, and evacuating soil gas under the foundation.

A tight foundation and a discharge system reduce the chimney or stack effect that draws air from the foundation or basement into the house. If radon levels are excessive, a passive discharge system can be connected. If further relief is needed, an inline duct fan can be installed in the discharge system (Figure 1).

Subslab depressurization effectively reduces radon concentrations to acceptable levels, even in houses with high concentrations (Dudney et al. 1988). This technique lowers pressure around the foundation envelope, causing the soil gas to be routed into a collection system and discharged to the outdoors.

A continuously operating fan should not be relied on as a discharge method. Ideally, a passive depressurization system should be installed, radon levels tested, and, if necessary, the system activated by adding a fan. The fan should be located in an accessible section of the stack so that any gas leaking from the positive-pressure side of the fan does not enter the living space.

Active subslab depressurization also raises some long-term concerns. If radon barrier techniques are not fully used, indoor air could be drawn into the basement and subsequently discharged, increasing energy costs. Durability is another concern, particularly with motor-driven components. Also, the system is susceptible to owner interference.

Walls

Low-Density Construction. The most common type of lightweight wall construction is the **wood frame** wall. Most houses in North America have exterior walls framed with wood studs, although steel studs offer several advantages; for example, they are more dimensionally stable and are truer than wood studs. Additionally, **steel studs** can be fabricated from recycled material and are themselves recyclable. However, these studs can create a significant thermal bridge across the cavity insulation, reducing its thermal
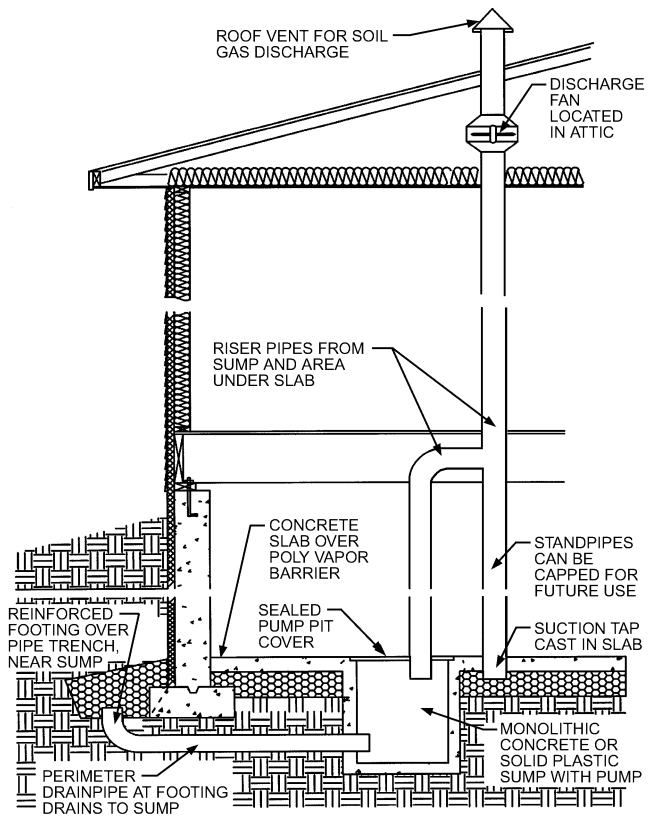
Fig. 1 Soil Gas Collection and Discharge Techniques

resistance by up to 50%. Different heat transfer between the framing member and cavities may lead to thermal anomalies with visual consequences (surface discoloration from drift accumulation, or ghosting). Insulated sheathing helps mitigate the effect of these differences. Additionally, light-gage steel construction has a lower moisture-storage capacity than wood, which can make steel-framed assemblies more sensitive to moisture infiltration.

The interior side of the framing is typically sheathed with gypsum wallboard. In cold-climate wood construction, to enhance the wall's energy efficiency, foam insulation sheathing can be applied between the gypsum board and the framing. An advantage of this practice is that the low-permeance sheathing can take the place of a vapor retarder. The disadvantage is that it complicates application of the gypsum board. Use of interior vapor retarders in warm, humid climates may be undesirable, and should be reviewed by the designer.

Cavities between framing members are filled with thermal insulation, including batt, loose fill, stabilized loose fill, site-injected foam, and rigid foam boards. With all products, the level of performance is related to the quality of the installation. Batts should be installed to completely fill the cavities along the back corners and the depth of the cavity. Gaps created by framing members or voids in an insulation caused by material settling or by improper installation can significantly reduce thermal performance. Dry loose fill should be installed at the manufacturer's recommended minimum density to avoid settling or the formation of voids. Wet loose fills should be installed with the proper amount of moisture, as recommended by the manufacturer. Stabilized loose fill insulations are applied with adhesive and water to prevent settling and movement within the cavity. As these products dry, some shrinkage has been observed; this can affect the wall's thermal performance. Before the cavity is sealed, enough time must be allowed to remove any excess water added by the application process. Site-injected foams are introduced with a hose and allowed to expand in the cavity and

interstitial spaces. Rigid foam board, sometimes used as an insulation material, is cut to size and placed tightly between studs.

Commonly used exterior sheathing materials include gypsum sheathing, plywood, oriented strand board (OSB), and foam insulating sheathing. For low-rise buildings, usually less than three stories, airflow retarders are installed on the outside of the exterior sheathing and covered with an exterior finish such as vinyl or aluminum siding, stucco, or brick.

Airflow can be retarded by constructing a continuous, air-impermeable plane at the sheathing surface (e.g., tongue-and-groove gypsum board with taped joints). The sheathing/window, sheathing/roof, and sheathing/floor junctions are also sealed.

When an insulating sheathing is used, vertical or horizontal spacer strips can be installed between the siding and sheathing to (1) provide a rain screen, (2) increase thermal resistance by maintaining an air space between the reflective foil on the sheathing and the siding, and (3) provide a nail base for the siding.

If the exterior finish is an **exterior insulation finishing system** (EIFS), a layer of insulation is attached to the exterior wall, and a synthetic glass-mesh-reinforced coating is attached to the insulation. An EIFS is usually applied by hand to the wall on site; it also can be prefabricated as panels in a factory.

Panelized walls are composed of an insulation layer faced on both sides with a sheathing material. The insulation layer ranges in thickness from 2 to 12 in. OSB is the most widely used sheathing material, but gypsum sheathing and plywood are also available. Because of evolving techniques for energy-efficient splines, panelized walls can have significantly fewer thermal bridges than wood frame construction.

Interior and exterior finishes for panelized walls are similar to those used in wood frame construction. Some panelized walls may already have suitably finished surfaces. Advantages of using panelized walls include (1) higher energy efficiency than typical wood frame wall systems, (2) little or no thermal bridging in the clear wall area, (3) tighter-than-average construction because of reduced jointing if large panels are used, and (4) integration of the insulation into the panel system, making insulation installation unnecessary. Potential problems with panelized walls are (1) facer delamination in improperly built assemblies, (2) fire safety concerns with the use of cellular plastics (an issue in *any* wall with insulating sheathing), and (3) insect control (carpenter ants have been reported to nest in hollows carved in the panels).

Masonry Construction. A common masonry wall is made with concrete masonry units (CMUs), blocks of concrete cast in various shapes and joined with mortar to form a wall. The concrete used to fabricate CMUs is produced with a variety of aggregates and typically varies in density from 85 to 135 lb/ft^3 (Andrews 1989). A CMU wall provides a finished, durable interior and exterior surface. Holes can be drilled through the wall for utility penetrations. Many CMUs are available with patterns cast into the exterior face, thus providing diverse exterior finishes. Interior or exterior sheathing, and/or an airflow retarder, can be applied to improve energy efficiency or to obtain a desired finish. However, water can leak through CMU walls into the building interior. Furthermore, moisture in the CMU can cause damage through freeze/thaw action. Exterior treatments can be used to reduce moisture pickup rates of CMUs.

If an EIFS is attached to the wall exterior, the insulation separates the wall from fluctuating outdoor temperatures. This method of insulation can be used to advantage in energy-efficient buildings in which the thermal energy stored in the wall mass is used to moderate indoor temperature swings. External placement also allows the wall cavity to be used for utilities that might be susceptible to freezing or heat loss. It is important that the edges of an EIFS be tightly abutted so that thermal bridges are minimized.

Steady-State Thermal Performance. James and Goss (1993) summarize heat transmission coefficient measurements and calculations for various wall, roof, ceiling, and floor systems. These data

are only for clear wall areas that do not include subsystems or the effects of joints created at intersections with another portion of the building envelope.

To test the validity of applying clear-wall data to the wall system, a series of three-dimensional heat conduction simulations was performed on a single-family, detached one-story house (Kosny and Desjarlais 1994). These simulations showed that, for a conventional 2 by 4 in. wood-frame wall system with studs installed on 16 in. centers, the average area-weighted whole-wall R-value was 91% of the clear-wall R-value. For a similar wall using 3.5 in. steel studs, the whole-wall R-value was 83% of the clear-wall R-value. A similar two-dimensional analysis of an attached two-story steel stud house by Tuluca et al. (1997) showed the R-value for the wall system to be 40 to 50% of the clear-wall R-value. Thermal bridging can occur through framing, metal ties through exterior sheathing, and exposed slab edges.

The thermal bridges created by webs of concrete masonry units dictate the maximum thermal efficiency that a CMU can attain. To reduce thermal bridging, blocks containing only two webs instead of the usual three have been used, and web cross section has been reduced by up to 40%. However, even such changes in block design have not significantly improved wall R-value. Applying lightweight concretes with significantly lower thermal conductivity effectively improves thermal performance of these masonry units (Kosny and Christian 1995a). The same strategy can be used for CMUs containing core-insulating inserts or insulation fill; insulating inserts in high-density concrete blocks are ineffective.

Dynamic Thermal Performance. The steady-state R-value traditionally used to measure energy performance of a building envelope does not accurately reflect the dynamic thermal behavior of all complex building envelope systems. Further information can be obtained in Chapters 24 and 32 of the 2005 *ASHRAE Handbook—Fundamentals*.

Moisture. Historically, the primary moisture control strategy for walls is to restrict moisture entry. Another approach to envelope design is to provide walls that balance entry with removal and that control accumulation and pressure differential.

Recognizing that lightweight wall systems can get wet or occasionally start out wet, the designer can promote weather protection and drying. A rain screen (Figure 2) can be placed immediately behind the exterior cladding to control rain penetration by providing a pressure-equalized air space, or a house wrap, which is vapor-permeable and water-impermeable, can be installed over the exterior sheathing to protect the wall from weather yet allow it to dry if necessary.

For heating-dominated climates, a vapor retarder at the interior surface is advisable. Moisture originates from the interior of the building and migrates into the wall until it reaches the interior vapor retarder, which is kept warm because it is inside the thermal envelope. In cooling-dominated climates, exterior sheathing of impermeable rigid insulation can act as a vapor diffusion retarder. Moisture outside the building moves into the wall until it reaches the exterior vapor retarder, which is kept warm because it is outside of the thermal envelope. As a general rule, to keep moisture condensation accumulation to a minimum, this first condensing surface must be kept above the dew point.

Air Movement. Uncontrolled air movement across walls increases space conditioning costs and may cause moisture to condense. **Air infiltration** is air movement from outside into the conditioned space. **Air exfiltration** is air movement from the conditioned space to the outside. **Air intrusion** is penetration of air into the building envelope without entirely crossing it. For example, outside air can penetrate a wall at sheathing joints, move around or through the insulation, and return to the outside. Similarly, inside air can penetrate a wall at electric outlets, move around or through the insulation, and return to the conditioned space. **Air leakage** designates any type or combination of air movement in and across the

WOOD SIDING
(LEAKY)

AIR SPACE
FORMED BY
FURRING
STRIPS (OPEN
TOP AND BOTTOM)

BUILDING PAPER/
SHEATHING
(TIGHT)

AIR SPACE OPEN AT
BOTTOM (INSECT SCREEN
MAY BE DESIRABLE AT
THIS LOCATION)
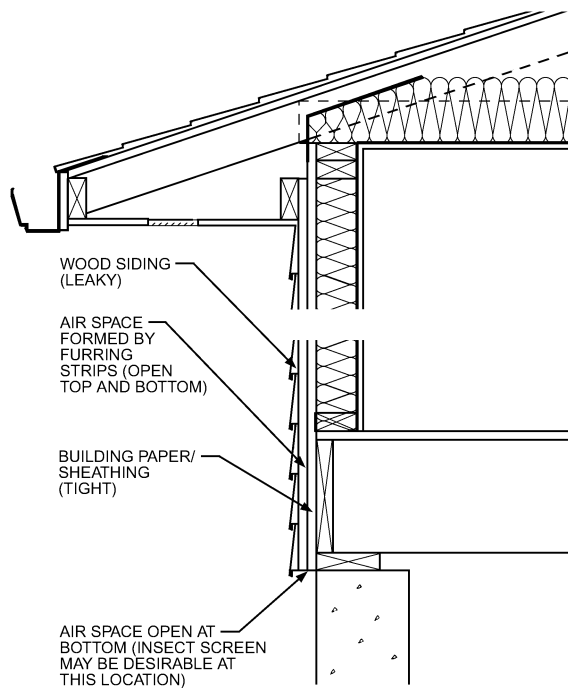
Fig. 2   Example of Rain Screen

envelope (see Chapter 27 of the 2005 *ASHRAE Handbook—Fundamentals*).

In general, an **air barrier** should be installed in walls. The air barrier reduces both infiltration and exfiltration. It also prevents intrusion by exterior or interior air, depending on the location of the air seal plane. Refer to Chapters 24 and 25 of the 2005 *ASHRAE Handbook—Fundamentals*.

In heating-dominated climates, the air barrier can be positioned on either the exterior or interior of the wall (e.g., framing). If placed to the exterior of stud construction that does *not* have insulating sheathing, the air barrier protects insulation located between framing members from cold air intrusion.

The air barrier can also be placed to the exterior of stud construction that has insulating sheathing, such as steel stud walls with fibrous insulation, gypsum board sheathing, rigid insulation sheathing, and brick finish. If the air barrier is on the winter-cold surface of the sheathing, it can be moisture-impermeable if the R-value of the rigid insulation is sufficient to maintain the air barrier above dew point during winter conditions. Impermeable air barriers are usually bituminous, rubber-based, or plastic membranes. However, the air barrier can also be composed of a gypsum board layer with the junctions taped and sealed. Masonry construction usually includes air-impermeable air barriers.

If the air barrier is placed to the interior of a wall in a heating-dominated climate, it protects the wall from intrusion by moist interior air. In theory, this type of barrier is more advantageous than an exterior barrier for structures where moisture condensation is likely, such as steel studs without insulating sheathing that surround a space with high humidity in winter. In practice, it is difficult to achieve a continuous air seal at the interior surface of a wall, especially in multistory buildings, because of the wall/floor and wall/ceiling junctions. A continuous air seal plane could be achieved by gypsum board with or without a polyethylene vapor retarder if particular attention is paid to details and with special construction supervision.

In hot, humid climates, the air barrier for air-conditioned buildings should be vapor-permeable if it is placed nearest the interior of the wall because the outside moist air can condense on cold interior surfaces. The exterior air barrier can be either moisture-permeable or moisture-impermeable. If the barrier is moisture-impermeable, the insulated layer near the conditioned space must have a sufficient R-value to keep the membrane above the dew point. This caveat applies to each component of the insulated layer separately.

In climates requiring significant heating and cooling, heating-dominated construction is usually indicated, but moisture accumulation calculations need to be performed if layers with low vapor permeance are used. In climates with some heating, significant cooling, and high humidity, it is usually prudent to avoid vapor-impermeable air barriers and layers with low vapor permeance on the interior of the wall assembly.

In general, except for prefabricated wall panels, two layers with low vapor permeance (e.g., an exterior vapor-impermeable airflow retarder and an interior vapor retarder) should be avoided because moisture can be trapped in the wall during construction or operation.

Roof and Ceiling Assemblies

Thermal Performance. In pitched roof assemblies, attic space is typically insulated with mineral fiber batts or blankets and/or mineral fiber or cellulose loose fill insulation. The total thermal resistance of the ceiling plus insulation, attic space, and roof is the sum of the conduction resistance of the ceiling plus insulation and the effective attic resistance. The roof resistance is generally negligible.

Thermal performance of the insulation varies with mean temperature. In winter, thermal resistance of the insulation increases; in summer, it decreases. In installing loose fill insulation, care must be taken to avoid overblowing the material to densities below the intended design density for a given R-value. At densities below design, the material may not deliver the desired R-value. To prevent overblowing, the correct amount of material for a given coverage area and R-value should always be installed. Manufacturers of loose fill insulation are required to provide maximum net coverage information on all product packaging. Some high-density loose fill products may gradually settle to a lower thickness after being installed. The reduced thickness decreases the thermal resistance despite the increased density. For materials subject to settling, initial installed and settled thickness information should be available on package labels or from manufacturers so that the desired settled R-values can be achieved.

Some low-density loose fill materials are porous enough that very low temperatures at the top of the insulation may lead to free convection in the insulation. For example, Wilkes et al. (1991) observed that effective thermal resistance decreased by nearly 50% from nominal values when temperature differences greater than 70°F were imposed. Free convection can be suppressed by placing a layer of batt insulation over the low-density loose fill insulation. Alternatively, batts or blankets can be installed first and the low-density loose fill blown in on top of the batts or blankets. Mineral fiber batts or blankets should be installed at the proper width so that there are no air gaps between the batts.

In a roof assembly over a ventilated attic space in a cooling-dominated climate, insulation may be supplemented by a **radiant barrier** of high-reflectance material to reduce radiant heat transfer between the hot roof and the relatively cool ceiling. The radiant barrier can be attached to roof rafters or fastened directly to the underside of the roof sheathing with the reflective surface facing down. Care should be taken to not disturb and damage existing insulation when retrofitting an attic with a radiant barrier. Also, dust decreases the effective reflectance of the radiant barrier over time; however, if the operative surface faces down, the reduction in thermal performance should be minimal.

During the cooling season, a radiant barrier reduces temperatures affecting the air, insulated surfaces, and HVAC ducts and equipment located in the attic space. A ventilated radiant barrier combined with an equally divided, continuous soffit and ridge vents provides optimal performance. The most cost-effective use of radiant barriers is

in cooling-dominated climates. Use of radiant barriers in other climates may result in a net annual increase in energy use because the beneficial attic heat gain in the noncooling seasons is lost. The U.S. Department of Energy (DOE 1991) compared the present-value savings of radiant barriers with those of conventional fibrous insulation for several climates and circumstances.

During the cooling season, a radiant barrier under the roof sheathing increases the efficiency of a duct system located in an attic (Hageman and Modera 1996). DOE (1991) does not consider this case.

With or without a radiant barrier, **powered ventilation** increases the effective attic resistance by reducing the temperature difference between the inside conditioned space and the attic space (see Table 5 in Chapter 25 of the 2001 *ASHRAE Handbook—Fundamentals*). However, this method is rarely cost-effective because of the energy cost of the fan. Additionally, powered ventilation can draw air from the conditioned space into the attic and, consequently, from the exterior to the interior space, subjecting it to increased sensible and latent loads associated with more air infiltration.

In low- or no-slope roofs, the insulation is a layered assembly comprising the deck, insulation, and membrane. Although there are relatively small gaps between the components, the high thermal resistance of the insulation keeps total heat flux low. However, heat flow through metal penetrations can be more than 1000 times greater than that through adjacent insulation. Therefore, the area of these thermal bridges should be kept small in proportion to the roof area. Minimizing this area may require interrupting potential bridges; for example, staggering fasteners that secure the insulation to the deck and those that attach the membrane to the insulation.

Moisture. In addition to moisture normally present in construction materials, moisture can be trapped in the roof and ceiling assembly from rain during construction, leaks that were not fixed before water entered the assembly, or reroofing over partially torn-off roofs. Additional moisture can enter a structure having no insulation vapor retarder. If porous insulation is used, water vapor can diffuse throughout the assembly. The amount of vapor may be insufficient to significantly affect the thermal conductivity of the insulation, but it may add a significant latent heat load. Diurnal temperature variations in the roof can cause water to evaporate, move as vapor through a porous system, and condense (Hedlin 1988). When conditions are right for this effect, heat flow from this factor alone can easily exceed normal conduction flows.

Air Movement. With pitched roofs, the attic normally is ventilated by airflow from the edges of the assembly, over the insulation, and out through continuous ridge vents or occasional vents in the roof or gable ends of the attic. Ventilation may be by natural or forced convection, but natural convection by a combination of continuous ridge vents and continuous soffit vents seems most effective. A type of low- or no-slope roof called a **ventilated cold-deck system** has vents at the eaves and at intervals over the roof to allow circulation of dry outside air over the insulation. The effectiveness of such vents is uncertain in regions with a cold or a temperate but humid climate (IEA 1994). An alternative is a **nonventilated cold-deck system** with a vapor retarder on the ceiling consisting of staggered strips of polyethylene on the bottom and top and exposed fabric between them. Vapor inside the building effectively "sees" a continuous layer of polyethylene because of the staggering. Condensed water wicks through the exposed fabric on the top to the exposed fabric on the bottom and evaporates to the inside (Pedersen et al. 1992).

FENESTRATION

Conduction/Convection and Radiation Effects

Heat transfer through a window resulting from a temperature differential between the inside and outside (i.e., conduction, convection, and radiation) is a complex and interactive phenomenon. Although the glass itself is a poor insulator, it is used effectively in

a window to create thin insulating air films on either side of single glazing or dead air/gas spaces between glazing layers. Glass can also decrease direct transmission of radiant energy from the room or ambient sources. Chapter 31 of the 2005 *ASHRAE Handbook—Fundamentals* discusses fenestration in much greater detail.

Examination of the modes of heat transfer in a double-glazed window indicates that approximately 70% of the heat flow is through radiation from one glazing layer to another (Arasteh et al. 1985; Selkowitz 1979). Although the glass blocks direct transmission of radiant energy, energy is still absorbed and reemitted. Low-emittance coatings that are transparent to the eye significantly reduce the amount of heat transfer through a glazing cavity.

With the radiation mode of heat transfer minimized, conductive and convective modes dominate. To reduce these modes, gases with low conductivity (e.g., argon or krypton) are used in low-emittance-coated, multiple-glazed windows. Triple or quadruple glazing layers can additionally reduce heat transfer. See Chapter 31 of the 2005 *ASHRAE Handbook—Fundamentals* for design information.

Air Infiltration Effects

Air infiltration is uncontrolled movement of air from the outside to the inside of a building. It is a function of the pressure difference between the inside and outside environments (which is a function of wind speed, inside/outside temperature differences, and mechanical air balance) as well as window sealing characteristics (Klems 1983; Weidt and Weidt 1980). The infiltration rate of a fenestration product is a function of its method of operating (if any), weatherstripping material used, and construction quality. See Chapter 27 of the 2005 *ASHRAE Handbook—Fundamentals* for design information.

Solar Gain

Solar gain through windows can play a significant role in the energy balance of a building. Glazings transmit, reflect, or absorb a given wavelength of solar radiation, depending on the glazing characteristics. Transmitted solar radiation contributes heat to a space. Absorbed solar radiation is reemitted and/or conducted either to the inside or to the outside (depending on the window's glazing system configuration). Reflected solar radiation does not contribute heat to a space (Arasteh et al. 1989). Clear glass, the most common glazing material, transmits fairly evenly across the solar spectrum. Tinted or heat-absorbing glass absorbs solar radiation and gives the glass a specific color. Some tints exhibit a significant degree of spectral sensitivity (i.e., they do not transmit, absorb, and reflect evenly across the solar spectrum). These types of glazings offer great flexibility and can be tailor-made for specific climates or uses (e.g., provide ample daylighting without overheating an interior space).

Interactions Between Thermal Loss and Solar Gain

In heating-dominated applications, solar gain can provide a significant amount of heat. In many cases, heat supplied by the window can offset that lost through the window. The amount depends on the site characteristics (e.g., how much solar gain is available, how cold the climate is) and window characteristics (e.g., its U-factor and how much incident solar radiation is transmitted).

Typical **passive** solar applications try to maximize the amount of solar heat gain by installing significant amounts of south-facing glass, which receives the most solar radiation during the winter (in the northern hemisphere). However, high-performance windows facing north in a heating-dominated climate can provide more solar gain to a space than heat loss (Arasteh et al. 1989; Dubrois and Wilson 1992; Sullivan et al. 1992).

Wall/Window Interface

Air infiltration at the wall/window interface can cause serious damage to surrounding building materials and even to remote

materials, depending on the leakage path. In cold climates, warm, humid inside air can condense in the wall cavity. The condensate can damage the interior finish, seals of glazing units, insulation, exterior cladding, and possibly structural elements. Cold-air infiltration can affect the health and comfort of occupants by creating a dry indoor environment, cold drafts, and condensation and mildew on inside window surfaces. Air infiltration can also allow rain to enter the wall. Many materials are installed by many trades at the wall/window interface, making it difficult to inspect and prone to leak. In warm, humid climates, leakage at the wall/window interface can result in interior fungal growth, distortion of interior window trim, and deterioration of interior gypsum wallboard.

Control of Air Leakage

Control of air leakage must be continuous across the entire building envelope to be effective. To ensure continuity at the window, components that control airflow must be unified.

In a masonry wall, a self-adhesive asphalt membrane fastened to the masonry makes the wall airtight. A bead of sealant preserves airtightness between the glazing unit and the inner part of the metal window frame. Thus, the asphalt membrane and inner part of the metal frame are the two materials joined to withstand large air pressure loads. The membrane is extended and mechanically clamped to the inner part of the frame.

Control of Moisture Diffusion

Vapor diffusion across a small gap at the window/wall junction causes little building damage under average environmental conditions. Moreover, typical interior finishes covering the joint, made of metal or plastic or painted drywall, offer some resistance to moisture diffusion.

Control of Heat Flow

Continuity of the plane of thermal insulation is important primarily to reduce the potential for condensation on interior surfaces of the window and the surrounding interior finish. Insulation can be inserted in the joint between the wall and the window frame to compensate for the expected differential movement between the frame and the wall rough opening.

Control of Surface Condensation

To reduce the potential for condensation on the interior surface of the glazing and the frame of windows, as well as on the surrounding interior finish of the wall, the inside surface temperature can be controlled in the following ways:

- Select windows with appropriate condensation resistance for new construction.
- Seal the wall/window interface and between the sash and frame of operable windows to keep air leakage to a minimum.
- Make the area of window frame exposed to the interior larger than the area exposed to the outside. Metal frame extensions on the inside have a higher resistance to condensation but contribute to heat loss.
- Reduce excessive interior humidity levels.

Control of Rain Entry

Applying the rain screen principle at the wall/window interface requires the same features as applying it to the wall: (1) an airflow retarder, (2) a rain deflector on the outside of the interface, (3) much more venting on the outside face of the interface than on the inside, and (4) a drainage path toward the outside.

The line of airtightness is on the inside of the assembly, so the assembly is protected from water, ultraviolet rays, and extremes of temperature. The rain deflector on the outside acts as a rain deterrent only, not as a watertight/airtight seal. A non-airtight rain deflector does not threaten the weathertightness of the system because

pressure differences across the rain deflector are small. The key is to maintain airtightness on the inside of the joint. With little pressure difference across the rain deflector and with good detailing for outward drainage of the cavity, rain entry in the wall should be minimal. The interface of an exterior wall air barrier and an interior fenestration air barrier must be carefully considered during design and may require site mock-ups to adequately determine the best solution.

Face Seal Approach

The face seal approach calls for perfect sealing of the outer face of the wall/window junction. This sealed surface protects against rain and air infiltration. The seal must remain perfect over time; its maintenance schedule is quite demanding. It is also complicated because water leaks can follow indirect paths for entry indoors, and in a large building, it may be difficult to trace these paths back to the entry points.

WALL/ROOF INTERFACE

Control of Air Leakage

In low-sloop roof configurations, the roofing membrane forms a plane of continuous airtightness and therefore can and should be connected to the wall airflow retarder. However, the wall airflow retarder could also be connected to other airtight roof components, such as the roof deck or the roof vapor retarder.

Many building systems provide for differential movement between the wall and roof assemblies; in those systems, a flexible airflow retarder connection is required at the location of the movement control joint. In all systems, the airflow retarder must withstand wind-induced pressures and fully adhere to a rigid, structurally adequate substrate.

Figure 3 shows an assembly that uses the concrete roof deck to achieve a continuous wall/roof airflow retarder. The retarder of the wall assembly is connected to the concrete slab using a sheet airflow retarder material. The connection between the wall and slab edge retarder sheets is designed to accommodate differential movement of the wall and roof.

Figure 4 shows a protected membrane roof assembly in which the roof membrane is an airflow retarder that extends over the edge of the roof perimeter to connect to the wall airflow retarder. A sheet metal backing is used around the roof deck perimeter for attachment and to provide for differential movement at the interface.

In some types of curtain walls, such as the wall in Figure 5, the air seal must be made continuous over the parapet wall. This
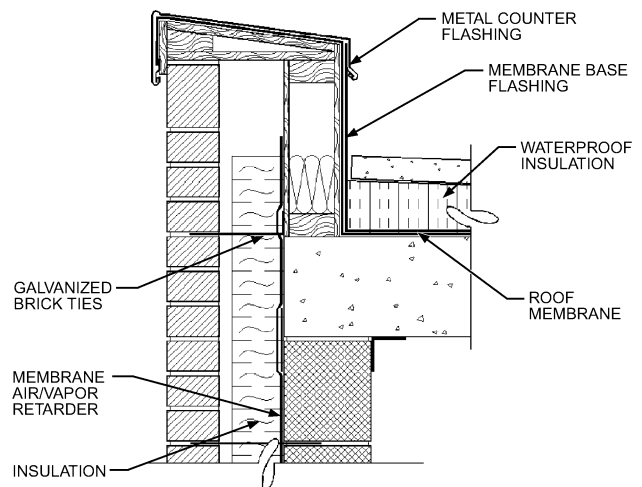
Fig. 3   Detail of Concrete Roof Deck with Continuous Wall/Roof Airflow Retarder
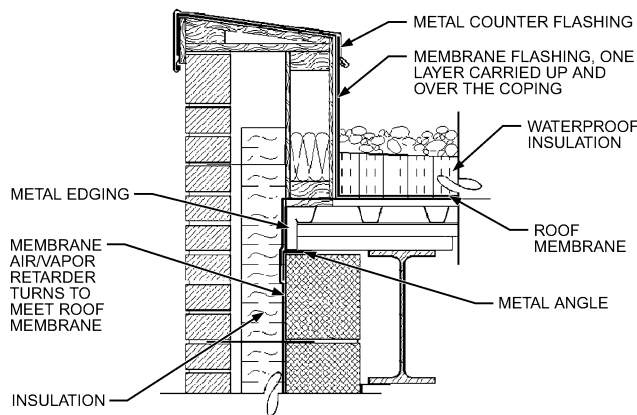
Fig. 4   Protected Membrane Roof Assembly
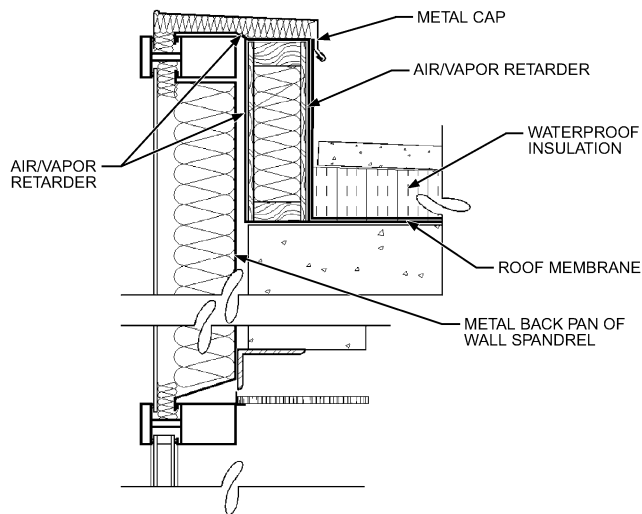
Fig. 5   Continuous Air Seal in Curtain Wall

allows connection of the wall air seal (the metal back pan of the spandrel panel) to the membrane flashing of the roof assembly or to the air/vapor retarder on the parapet, as in asphalt and roofing felt systems.

Control of Moisture Diffusion

The vapor retarder can also act as an airflow retarder, as shown in Figure 5, in which the metal back pan of the wall spandrel connects to the air/vapor retarder membrane on the parapet upstand wall. Because the parapet is encased in vapor retarder sheets, it must be kept dry before it is enclosed because any moisture left in the parapet cannot disperse. A vapor retarder with wicking properties could provide a better solution.

Control of Condensation

Condensation at the connection between the roof and wall can occur in interstitial spaces because of a lack of continuity in either system. Condensation also occurs if the vapor retarder temperature falls below the dew point of the air on the high-vapor-pressure side. Thus, thermal insulation applied to the exterior (winter-cold surface) of the vapor retarder must be sufficient to ensure that the temperature at the retarder plane remains higher than the dew point of the air. The temperature of the interior space between the exterior wall system and the parapet upstand wall often falls below the temperature of the interior inhabited space because of poor air circulation above the ceiling. Therefore, insulation applied over the parapet

cap and upstand wall may need to have greater thermal resistance than insulation for the wall or roof.

In exterior insulated wall systems (e.g., an EIFS or a curtain wall), thermal bridging must be minimized to control condensation between the parapet cap and the parapet upstand wall.

THERMAL BRIDGES IN BUILDINGS

A **thermal bridge** is an envelope area with a significantly higher rate of heat transfer than the contiguous enclosure. An example of thermal bridging is a steel truss in an attic with glass fiber insulation placed between trusses. The thermal conductivity of steel is about 1000 times greater than that of glass fiber insulation, so strong thermal bridging results along the trusses. In most construction details, the ratio between the high- and low-conductivity areas is smaller. An uninsulated CMU wall with brick facing could have a U-factor of 0.33 Btu/h·ft^2·°F if the CMU is made with sand and gravel aggregate. A concrete column located within that wall has a U-factor about 50% higher. This higher conductivity may justify classifying the column as a thermal bridge, but in typical construction this classification is relevant only if the concrete column proves to be detrimental for reasons other than energy use (e.g., moisture condensation).

Thermal bridges can be created by conduction, as in the previous examples, by radiation, by convection, or by a combination of those three modes of heat transfer (Silvers et al. 1985). Strong radiation effects occur, for instance, in an uninsulated brick wall retrofitted with metal cladding. The cladding is placed at some distance from the exterior of the brick wythe. The warmer brick wall radiates to the cold metal sheet. The different temperatures of the two surfaces also engender air convection.

Detrimental Effects of Thermal Bridges

Thermal bridges increase energy use, promote moisture condensation in and on the envelope, and create nonuniform temperatures in conditioned spaces. Comparison between the uninsulated slab edge detail of Figure 6A and the version with slab edge insulation with an R-value of 10 ft^2·°F·h/Btu in Figure 6B illustrates the importance of designing to reduce thermal bridging. [Refer to Steven Winter Associates (1988) for numerical examples summarized in this section.] This example, and the others in this section, use the term **total R-value**, where $R_t = 1/U$; R_t includes the effect of exterior and interior air films.

- **Increased energy use.** The portion of the wall that extends from the top of the slab edge to the shelf angle (Figure 6A) has $R_t = 2.3$ ft^2·°F·h/Btu when the wall insulation is furred in. Moving the insulation into the wall cavity (Figure 6B) increases R_t by about 2.2 times, to 5.3 ft^2·°F·h/Btu.
- **Damage to structural components.** On cold days, the uninsulated wall area collects moisture on the interior surface of the steel beam and on the slab underside. At 20°F outside air temperature, 70°F indoor air temperature, and 50% indoor relative humidity, moisture condenses on about 0.66 ft^2 of beam and slab for every linear foot of wall. This condensation can rust the metal beam and, if it penetrates the concrete block, can rust the brick ties. The insulated detail (Figure 6B) generates moisture condensation only on the bottom flange of the beam.
- **Damage to interior finishes.** Moisture can drip from the slab underside and from the steel beam, staining ceiling tiles and resulting in higher maintenance costs and loss of rental value. These effects are specific to the heating season and are magnified when thermal bridging is accompanied by air leakage, because air transports and deposits moisture on thermal bridges.

In cold and temperate climates, thermal bridges may slightly decrease peak cooling load and cooling energy use. In hot climates, this effect could be reversed. When the climate is hot and humid,
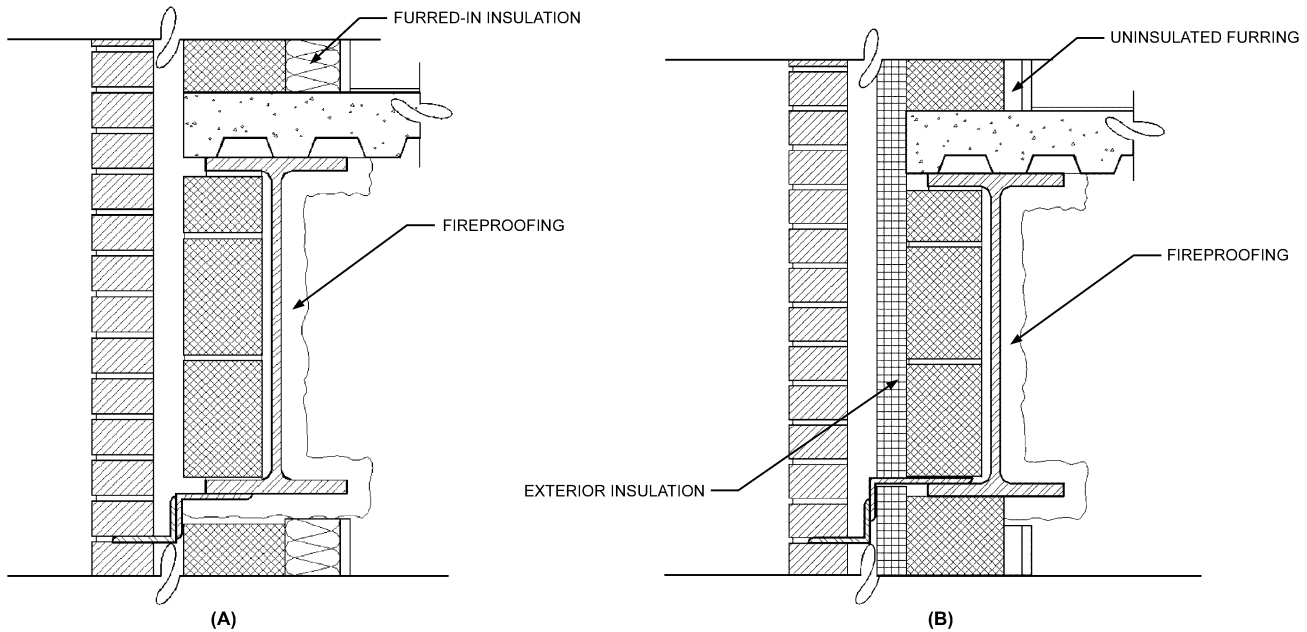
Fig. 6 Detail of (A) Uninsulated and (B) Insulated Slab Edge and Metal Shelf Angle
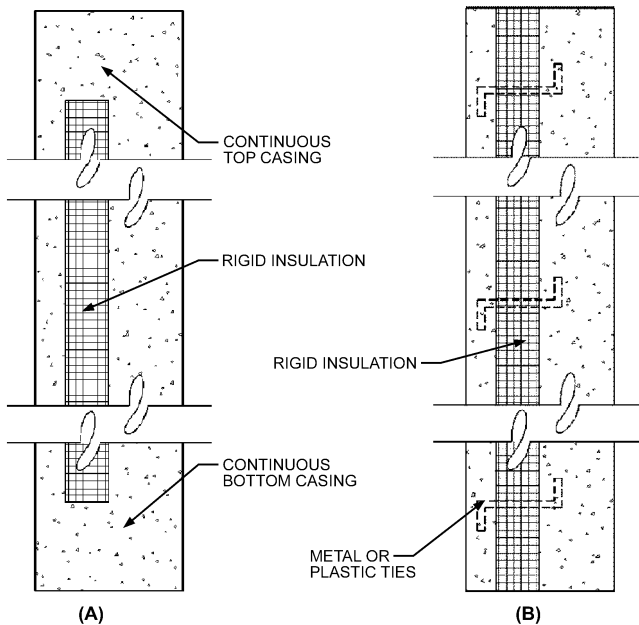
Fig. 7 Sandwich Panel with Insulation Encased in Concrete

Fig. 8 Steel Studs in Insulated Wall with Ceramic Finish

moisture condensation can create problems if the building is air conditioned or refrigerated.

Thermal Bridge Mitigation

Primary causes for conduction thermal bridging are (1) high thermal conductivity and (2) geometries that create zones where large exterior surfaces connect to much smaller interior surfaces. Thermal bridges can sometimes be eliminated, but usually they can be mitigated to create systems with significantly lower U-factors. Examples of conduction thermal bridges and mitigating details follow:

• **Factory-produced components with high conductivity**
Sandwich panel with insulation fully encased in concrete (Figure 7A). One possible solution is to connect the exterior and interior wythes of the panel with metal or plastic tie rods (Figure 7B).

This 6 ft high sandwich panel has a 3 in. extruded polystyrene core completely encased in concrete. The concrete has a conductivity over 50 times higher than that of polystyrene, resulting in $R_t = 5.4$ ft$^2 \cdot$°F·h/Btu. Moisture can collect on the top and bottom concrete edges of the panel. For $T_{OA} = 20$°F, $T_{IA} = 70$°F, and 50% rh, about 20% of the panel area can be covered with moisture.

When the interior and exterior concrete wythes are attached with metal or plastic tie rods, R_t of the panel increases by a factor of almost 3 to 15.1 ft$^2 \cdot$°F·h/Btu or 16 ft$^2 \cdot$°F·h/Btu, respectively. No moisture condensation on interior surfaces is likely.

• **Assemblies that contain high-conductance components**
Steel studs in insulated wall. One possible solution: Provide insulating sheathing (Figure 8).

This steel stud wall is used in low-cost multifamily, commercial, and industrial construction. The exterior gypsum board is provided for fire protection. If the wall has R-11 insulation, the studs reduce the
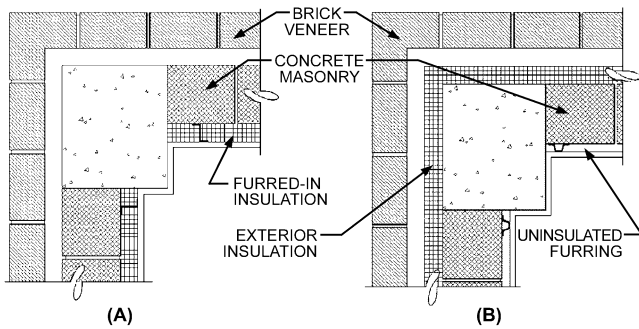
Fig. 9 Details of Insulation Around Column in Masonry Wall

wall R_t to 7.75 ft^2·°F·h/Btu. For $T_{OA} = 20$°F, $T_{IA} = 70$°F, and 50% rh, every linear foot of steel stud can generate 0.15 ft^2 of moisture condensation on the interior surface of the gypsum wallboard.

Extruded polystyrene sheathing 1 in. thick placed on the winter-cold surface of the gypsum board sheathing reduces thermal bridging, resulting in $R_t = 14.5$ ft^2·°F·h/Btu. For $T_{OA} = 20$°F, $T_{IA} = 70$°F, and 50% rh, moisture is less likely to condense on interior surfaces. If polystyrene is placed on the steel studs directly, the increase in R-value is even higher because the lateral heat flow is reduced.

If all insulation is placed on the exterior surface of the steel studs, the studs are kept at a temperature close to that of the conditioned space. Moisture condensation is practically eliminated. This solution merits special consideration in spaces with high relative humidity, such as kitchens and pool buildings.

- **Junction between envelope systems achieved with high-conductance components**

   Uninsulated slab edge and metal shelf angle, at junction between CMU wall and concrete floor (see Figure 6A). One possible solution is to place insulation in the wall cavity (Figure 6B).

   This detail shows an uninsulated slab edge and perimeter metal beam in a CMU/brick wall. For the wall segment that extends from the top of the slab edge to the shelf angle, $R_t = 2.3$ ft^2·°F·h/Btu. For $T_{OA} = 20$°F, $T_{IA} = 70$°F, and 50% rh, about 0.66 ft^2 of slab underside and steel beam could collect moisture along every linear foot of slab edge.

   The improved detail of Figure 7B uses R-10 rigid insulation in the wall cavity. The perimeter metal beam would be insulated, and the shelf angle remains as the only significant thermal bridge. The new total R-value of the wall segment is about 2.2 times higher (i.e., $R_t = 5.3$ ft^2·°F·h/Btu). Less moisture would be expected to condense along the slab edge.

   Insulation is sometimes specified on the interior surface of the perimeter beam in an effort to increase the thermal resistance of this wall segment. Site conditions rarely allow the installation to be thorough, so the top and bottom flanges remain exposed, creating a strong thermal bypass and marginalizing the effectiveness of the insulation. Moreover, the insulation makes vapor condensation more likely because it decreases the temperature of the beam chord but does not stop water vapor migration.

- **Combinations of geometry with high conductivity**

   Column in masonry wall with insulation located in steel stud furring (Figure 9A). One possible solution is to move the insulation in the wall cavity (Figure 9B).

   Concrete columns within masonry walls are often left uninsulated. In this example, a 12 by 12 in. column is located at the junction of two exterior walls composed of 6 in. CMU and 4 in. brick. The walls are insulated with $R = 10$ ft^2·°F·h/Btu polystyrene on metal furring. The corner, which includes the column and two CMU blocks on each side, has $R_t = 6$ ft^2·°F·h/Btu. This is 38% lower than the total R-value of the wall without the column ($R_t = 9.7$ ft^2·°F·h/Btu). For

$T_{OA} = 20$°F, $T_{IA} = 70$°F, and 50% rh, every linear foot of column could collect moisture on about 0.8 ft^2 of interior surfaces.

If the insulation is placed in the wall cavity, the total R-value of the corner more than doubles, to $R_t = 12.3$ ft^2·°F·h/Btu. No moisture condensation would be expected on interior surfaces of the column for the given temperature and relative humidity conditions.

Design Recommendations

These basic design principles apply to any thermal bridge.

Consider the combined effects of thermal bridging, air leakage, moisture condensation, and water intrusion. If one of these mechanisms of heat and mass transfer is involved, another one is commonly combined with it in a destructive synergy. In devising a solution for thermal bridging, ensure that moisture condensation is not increased. In climates with significant heating, this is of special concern for insulation placed on the interior (winter-warm) surface of materials with low vapor permeance, such as CMU or steel beam. In hot, humid climates, the concern relates to insulation placed on the summer-hot surface of materials with low vapor permeance.

In addition, because many thermal bridges are discontinuities in the envelope system, the chance that air will enter the envelope along these paths should be assessed. To cause damage, air does not need to infiltrate into a space from outdoors or to exfiltrate from a space to the outside; it is sufficient that air intrude in the envelope. For example, outside air can enter a stud wall cavity, short-circuiting the insulation and intensifying the thermal bridging effect, after which it exits again to the outside. In another example, indoor air can seep from the conditioned space into a furred-in CMU wall, behind the insulation and vapor retarder, increasing the chance for moisture condensation on the CMU surface. Of all forms of air intrusion, exfiltration of moist air along thermal bridge surfaces can be the most damaging. Note that the entry and exit points of air in the envelope can be distant.

It is particularly important to reduce thermal bridging, air intrusion, and moisture condensation if the following conditions are true:

- The building or spaces in it have uses that are likely to generate a relatively high amount of moisture during winter; examples are residences, hospitals, nursing homes, restaurants, kitchens, natatoriums, and bathrooms.
- The building is located in an area that experiences cold winters or sustained periods of cold during moderate winters. Climates with humid winters with subfreezing periods can also create problems.
- The building is located in a warm but not dry or arid climate and has uses that require low temperatures (e.g., refrigeration), or it is located in a hot, humid area and has uses that require air conditioning.

Consider the potential for thermal bridging and air intrusion during schematic design when decisions about the envelope system are made. Some systems are inherently more difficult to insulate and airproof, and changes during design development may create budget problems.

Use reasonably accurate methods to determine the effect of thermal bridging. Accurate formulas are available for most steel stud configurations (Kosny and Christian 1995b), but they are not sufficiently accurate for many other construction types. Two- and three-dimensional models are available and provide better results.

In mitigating a thermal bridge, several techniques can be used, often in combination. Such techniques include

- Change the thermal bridge material to one with lower conductivity. Plastic ties nearly eliminate thermal bridging in concrete sandwich panels.
- Decouple the thermal bridging elements from the rest of the construction. If the steel stud furring is detached from the CMU wall, the pathway between two materials with high conductivity is bro-
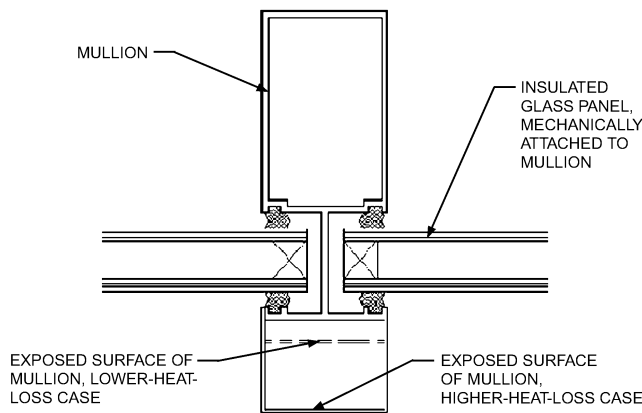
Fig. 10   Mullion with Deep Exterior Projection
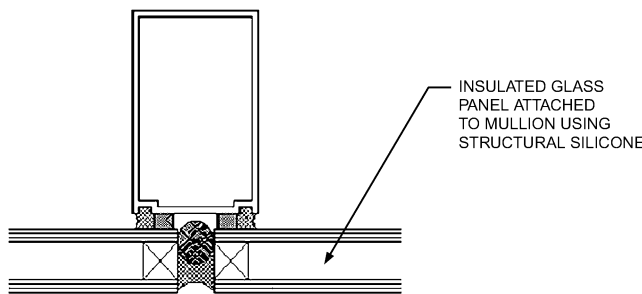
Fig. 11   Mullion Without Exterior Projection

ken. The best method to achieve the decoupling is to insert a thin, low-conductivity material, such as foam tape, at each stud. If an air space is created between the insulated steel stud layer and the CMU wythe, air convection can short-circuit the insulation.

- Change the geometry that creates thermal bridging. Figure 10 shows a mullion with a deep exterior projection. This projection acts like a fin during winter, enhancing the heat loss. One method of reducing the thermal bridging effect is to reduce the exterior projection (Figure 10, dashed line). If this is not acceptable for aesthetic reasons, implement a better thermal break system.
- Insulate the thermal bridge. For example, use insulating sheathing for steel stud walls.
- Change the insulation system. For example, a furred-in masonry wall with all insulation located in the furring could be changed to a masonry wall with rigid insulation on the exterior (winter-cold) surface of the CMU.
- Change the construction system. In a natatorium, for instance, structural silicone glazing without an exterior projection (Figure 11) might avoid moisture condensation on mullions.

THERMAL MASS

Thermal mass describes the ability of a material layer to store thermal energy and the ability of an opaque envelope component to dampen and delay transfer of heat and temperatures. That damping, if combined with moderate glazing, effective solar shading, a correct ventilation strategy, and inside partitioning with high thermal storage, helps moderate indoor temperature fluctuation under outdoor temperature swings (Brandemuehl et al. 1990). Increased thermal mass may also positively affect energy efficiency (Kosny et al. 1998; Newell and Snyder 1990; Wilcox et al. 1985). Finally, increased thermal mass may help shift demand for heating and cooling to off-peak periods.

The ability to store thermal energy in a layer primarily depends on the material's heat absorption coefficient:

Table 1   Typical Densities, Thermal Diffusivities, and Specific Heats of Common Building Materials

Description	Density, lb/ft^3	Thermal Diffusivity, ft^2/h	Specific Heat, Btu/lb·°F
Concrete	40 to 140	0.08 to 0.30	0.22
Steel	484	0.038	0.12
Wood	22 to 44	0.005 to 0.006	0.40
Insulation	0.6 to 2.0	0.027 to 0.22	0.2 to 0.38

$$b = \sqrt{\rho c k} \qquad (1)$$

where k is thermal conductivity, ρ is density, and c is specific heat capacity. See Table 1 and Chapter 25 of the 2005 *ASHRAE Handbook—Fundamentals* for values of these properties. The amount of thermal energy stored in a layer is governed by the **heat capacity**, the product of the layer's mass and its specific heat capacity:

$$Q_{stored} = (\rho d)c \qquad (2)$$

where d is the layer thickness.

Damping and time delay are defined by the way an opaque envelope component is composed. Best results are achieved when the thermal insulation faces the outside and the layers with largest heat capacity face the inside, as confirmed by an in-depth study of six wall configurations by Kosny et al. (1998). The damping capability of such a wall also increases with thermal resistance (Van Geem 1986).

Hourly-based computer simulations using transient energy simulation tools may produce a fair understanding of the complex interactions that exist between the (1) surface, type, and orientation of the glazing; (2) effectiveness of the solar shading used; (3) ventilation strategy adopted; (4) heat storage capacity of the internal partitions; (5) damping effect of all opaque envelope components; and (6) HVAC set point and control policies implemented with stable inside temperature and energy consumed for heating and cooling. However, a harmonic analysis at room level, using the transient harmonic wall properties defined in Chapter 23 of the 2005 *ASHRAE Handbook—Fundamentals*, helps in understanding part of these interactions.

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CHAPTER 44

BUILDING AIR INTAKE AND EXHAUST DESIGN

FRESH air enters a building through its air intake. Likewise, building exhausts remove air contaminants from a building so wind can dilute the emissions. If the intake or exhaust system is not well designed, contaminants from nearby outside sources (e.g., vehicle exhaust) or from the building itself (e.g., laboratory fume hood exhaust) can enter the building with insufficient dilution. Poorly diluted contaminants may cause odors, health impacts, and reduced indoor air quality. This chapter discusses proper design of exhaust stacks and placement of air intakes to avoid adverse air quality impacts. Chapter 16 of the 2005 *ASHRAE Handbook—Fundamentals* more fully describes wind and airflow patterns around buildings. Related information can also be found in Chapters 7, 15, 30, 31, and 32 of this volume, Chapters 12 and 13 of the 2005 *ASHRAE Handbook—Fundamentals*, and Chapters 24, 25, and 30 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*.

EXHAUST STACK AND AIR INTAKE DESIGN STRATEGIES

Stack Design Strategies

The dilution a stack exhaust can provide is limited by the dispersion capability of the atmosphere. Before discharge, exhaust contamination should be reduced by filters, collectors, and scrubbers.

Central exhausts that combine flows from many collecting stations should always be used where safe and practical. By combining several exhaust streams, central systems dilute intermittent bursts of contamination from a single station. Also, the combined flow forms an exhaust plume that rises a greater distance above the emitting building. Additional air volume can be added to the exhaust near the exit with a makeup air unit to increase initial dilution and exhaust plume rise. This added air volume does not need heating or cooling, saving on energy costs.

In some cases, separate exhaust systems are mandatory. The nature of the contaminants to be combined, recommended industrial hygiene practice, and applicable safety codes need to be considered. Separate exhaust stacks could be grouped in a tight cluster to take advantage of the larger plume rise of the resulting combined jet. Also, a single stack location for a central exhaust system or a tight cluster of stacks allows building air intakes to be positioned as far as possible from the exhaust. For a tight cluster to be considered as a single stack in dilution calculations, the stacks must be uncapped, have approximately the same exhaust velocities, and all lie within a two-stack diameter radius of the middle of the group. Stacks lined up in a row do not act as a single stack (Gregoric et al. 1982).

As shown in Figure 1, stack height h_s is measured above the roof level on which the air intake is located. Wilson and Winkel (1982) demonstrated that stacks terminating below the level of adjacent walls and architectural enclosures frequently do not effectively reduce roof-level exhaust contamination. To take full advantage of their height, stacks should be located on the highest roof of a building.

Architectural screens used to mask rooftop equipment adversely affect exhaust dilution, depending on porosity, relative height, and
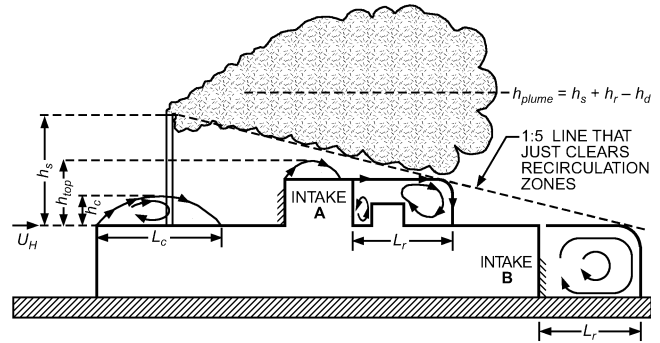
Fig. 1 Flow Recirculation Regions and Exhaust Parameters
(Wilson 1982)

distance from the stack. Petersen et al. (1999) found that exhaust dispersion improves with increased screen porosity.

Large buildings, structures, and terrain close to the emitting building can adversely affect stack exhaust dilution, because the emitting building can be within the recirculation flow zones downwind of these nearby flow obstacles (Wilson et al. 1998a). In addition, an air intake located on a nearby taller building can be contaminated by exhausts from the shorter building. Wherever possible, facilities emitting toxic or highly odorous contaminants should not be located near taller buildings or at the base of steep terrain.

As shown in Figure 2, stacks should be vertically directed and uncapped. Stack caps that deflect the exhaust jet have a detrimental effect on exhaust plume rise. Small conical stack caps often do not completely exclude rain, because rain does not usually fall straight down; periods of heavy rainfall are often accompanied by high winds that deflect raindrops under the cap and into the stack (Changnon 1966). A stack exhaust velocity V_e of about 2500 fpm prevents condensed moisture from draining down the stack and keeps rain from entering the stack. For intermittently operated systems, protection from rain and snow should be provided by stack drains, as shown in Figure 2F to 2J, rather than stack caps.

Recommended Stack Exhaust Velocity

High stack exhaust velocity and temperatures increase plume rise, which tends to reduce intake contamination. Exhaust velocity V_e should be maintained above 2000 fpm (even with drains in the stack) to provide adequate plume rise and jet dilution. Velocities above 2000 fpm provide still more plume rise and dilution, but above 3000 to 4000 fpm, noise and vibration from exhaust fans become an important concern. An exit nozzle (Figure 2B) can be used to increase exhaust velocity and plume rise. Many laboratory fume hood systems use variable-volume fans that reduce flow from hoods when they are closed. Stack exhaust velocity calculation must be based on the minimum total flow rate from the system, not the maximum.

An exception to these exhaust velocity recommendations may be when corrosive condensate droplets are discharged. In this case, a velocity of 1000 fpm in the stack and a condensate drain are recommended to reduce droplet emission. At this low exhaust velocity, a

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The preparation of this chapter is assigned to TC 4.3, Ventilation Requirements and Infiltration.
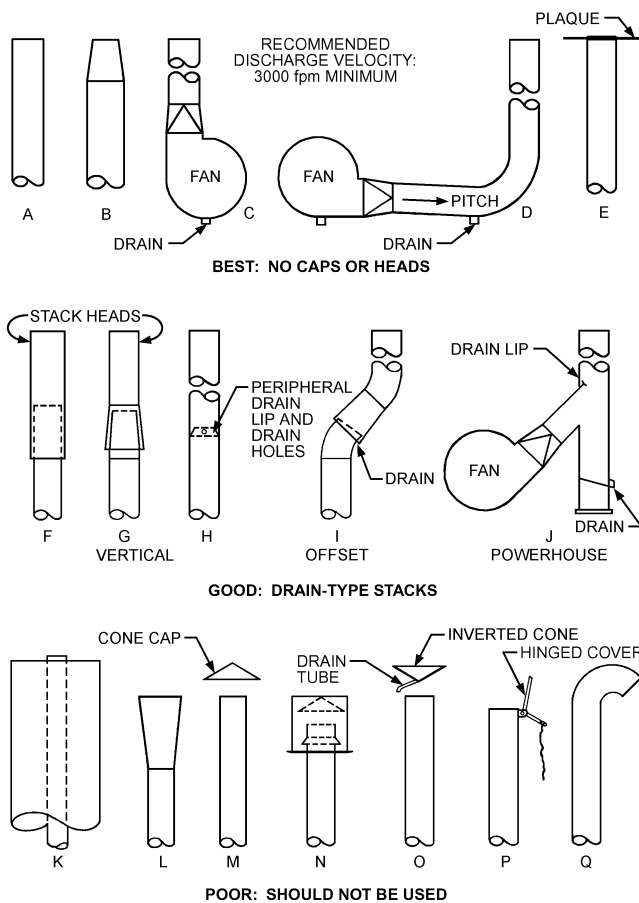
Fig. 2 Stack Designs Providing Vertical Discharge and Rain Protection
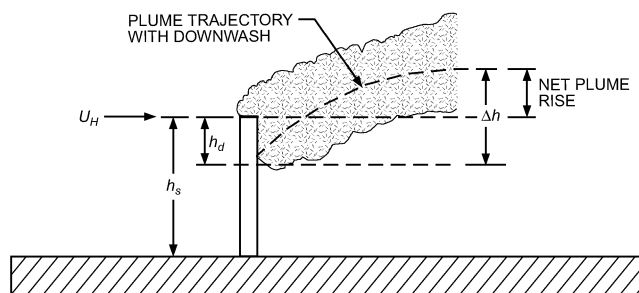
Fig. 3 Reduction of Effective Stack Height by Stack Wake Downwash

taller stack may be needed to counteract downwash caused by low exit velocity.

Stack wake downwash occurs where low-velocity exhausts are pulled downward by negative pressures immediately downwind of the stack, as shown in Figure 3. V_e should be at least 1.5 times the design speed U_H at roof height in the approach wind to avoid stack wake downwash. A meteorological station design wind speed U_{met} that is exceeded less than 1% of the time can be used. This value can be obtained from Chapter 28 of the 2005 *ASHRAE Handbook—Fundamentals*, or estimated by applying Table 2 of Chapter 16 of that volume to annual average wind speed. Because wind speed increases with height, a correction for roof height should be applied for buildings significantly higher than 30 ft, using Equation (4) and Table 1 of Chapter 16 of the 2005 *ASHRAE Handbook—Fundamentals*.

Other Stack Design Standards

Minimum heights for chimneys and other flues are discussed in the *International Building Code* (ICC 2006). For laboratory fume hood exhausts, American Industrial Hygiene Association (AIHA) *Standard* Z9.5 recommends a minimum stack height of 10 ft above the adjacent roof line, an exhaust velocity V_e of 3000 fpm, and a stack height extending one stack diameter above any architectural screen; National Fire Protection Association (NFPA) *Standard* 45 specifies a minimum stack height of 10 ft to protect rooftop workers. Toxic chemical emissions may also be regulated by federal, state, and local air quality agencies.

Air Intake Locations to Minimize Contamination

Carefully placed outside air intakes can reduce stack height requirements and help maintain acceptable indoor air quality. Rock and Moylan (1999) review recent literature on air intake locations and design. Petersen and LeCompte (2002) also showed the benefit of placing air intakes on building sidewalls.

ASHRAE *Standard* 62.1-2004 highlights the need to locate makeup air inlets and exhaust outlets to avoid contamination.

Outside contamination sources to consider include the following:

Toxic Stack Exhausts. Boilers, emergency generators, and laboratory fume hoods are some sources that can seriously affect building indoor air quality because of toxic air pollutants. These sources, especially diesel-fueled emergency generators, can also produce strong odors that may require administrative measures, such as generator testing during low building occupancy or temporarily closing the intakes.

Automobile and Truck Traffic. Heavily traveled roads and parking garages emit carbon monoxide, dust, and other pollutants. Diesel trucks and ambulances are common sources of odor complaints (Smeaton et al. 1991). Intakes near vehicle loading zones should be avoided. Overhead canopies on vehicle docks do not prevent hot vehicle exhaust from rising to intakes above the canopy. When the loading zone is in the flow recirculation region downwind from the building, vehicle exhaust may spread upwind over large sections of the building surface (Ratcliff et al. 1994). Garbage containers may also be a source of odors, and garbage trucks may emit diesel exhaust with strong odors.

Kitchen Cooking Hoods. Kitchen exhaust can be a source of odors and cause plugging and corrosion of heat exchangers. Grease hoods have stronger odors than other general kitchen exhausts. Grease and odor removal equipment beyond that for code requirements may be needed if air intakes cannot be placed far away.

Evaporative Cooling Towers. Outbreaks of Legionnaires' disease have been linked to bacteria in cooling tower drift droplets being drawn into the building through air intakes (Puckorius 1999). ASHRAE *Guideline* 12 gives advice on cooling tower maintenance for minimizing the risk of Legionnaires' disease, and suggests keeping cooling towers as far away as possible from intakes, operable windows, and outside public areas. No specific minimum separation distance is provided or available. Prevailing wind directions should also be considered to minimize risk. Evaporative cooling towers can have several other effects: water vapor can increase air-conditioning loads, condensing and freezing water vapor can damage equipment, and ice can block intake grilles and filters. Chemicals added to retard scaling and biological contamination may be emitted from the cooling tower, creating odors or health effects, as discussed by Vanderheyden and Schuyler (1994).

Building General Exhaust Air. General indoor air that is exhausted will normally contain elevated concentrations of carbon dioxide, dust, copier toner, off-gassing from materials, cleaning agents, and body odors. General exhaust air should not be allowed to reenter the building without sufficient dilution.

Stagnant Water Bodies, Snow, and Leaves. Stagnant water bodies can be sources of objectionable odors and potentially harmful organisms. Poor drainage should be avoided on the roof or ground near the intake. Restricted airflow from snow drifts, fallen leaves, and other debris can be avoided in the design stage with elevated louvers above ground or roof level.

Rain and Fog. Direct intake of rain and fog can increase growth of microorganisms in the building. AMCA (2003) recommends selecting louvers and grilles with low rain penetration and installing drains just inside the louvers and grilles. In locations with chronic fog, some outside air treatment is recommended. One approach is to recirculate some part of the indoor air to evaporate entrained water droplets, even during full air-side economizer operation (maximum outside air use).

Environmental Tobacco Smoke. Outside air intakes should not be placed close to outside smoking areas.

Plumbing Vents. Codes frequently require a minimum distance between plumbing vents and intakes to avoid odors.

Smoke from Fires. Smoke from fires is a significant safety hazard because of its direct health effects and from reduced visibility during evacuation. NFPA *Standard* 92A discusses the need for good air intake placement relative to smoke exhaust points.

Construction. Construction dust and equipment exhaust can be a significant nuisance over a long period. Temporary preconditioning of outside air is necessary in such situations, but is rarely provided. A simple solution is to provide room and access to the outside air duct for adding temporary air treatment filters or other devices, or a sufficient length of duct so that such equipment could be added when needed. Intake louvers and outside air ducts also require more frequent inspections and cleaning when construction occurs nearby.

Vandalism and Terrorism. Acts of vandalism and terrorism are of increasing concern. Louvers and grilles are potential points of illegal access to buildings, so their placement and construction are important. Intentional introduction of offensive or potentially harmful gaseous substances is also of concern. Some prudent initial design considerations might be elevating grilles and louvers away from easy pedestrian access and specifying security bars and other devices. Also, unlocked stair tower doors required for roof access during emergency evacuations may limit use of rooftop air intakes in sensitive applications because individuals would have ready access to the louvers. For more information, see ASHRAE's (2003) *Risk Management Guidance for Health, Safety, and Environmental Security under Extraordinary Incidents*.

General Guidance on Intake Placement

Experience provides some general guidelines on air intake placement. As a rule, intakes should never be located in the same architectural screen enclosure as contaminated exhaust outlets, especially low-momentum exhausts (which tend to be trapped in the wind recirculation zone within the screen). For more information, see the section on Influence of Architectural Screens on Exhaust Dilution.

If exhaust is discharged from several locations on a roof, intakes should be sited to minimize contamination. Typically, this means maximizing separation distance. Where all exhausts of concern are emitted from a single, relatively tall stack or tight cluster of stacks, a possible intake location might be close to the base of this tall stack, if this location is not adversely affected by other exhaust locations, or is not influenced by tall adjacent structures creating downwash. However, contaminant leakage from the side of the stack has been observed in positively pressurized areas between the exhaust fans and stack exit (Hitchings 1997; Knutson 1997), so air intakes should not be placed very close to highly toxic or odorous exhaust stacks regardless of stack height.

Intakes near vehicle loading zones should be avoided. Overhead canopies on vehicle docks do not effectively protect air intakes, and vehicle exhaust may spread over large sections of the building surface. Loading zones also may have garbage and solid waste
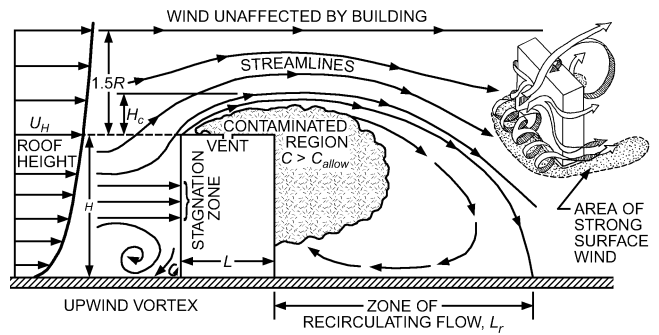
Fig. 4   Flow Patterns Around Rectangular Building
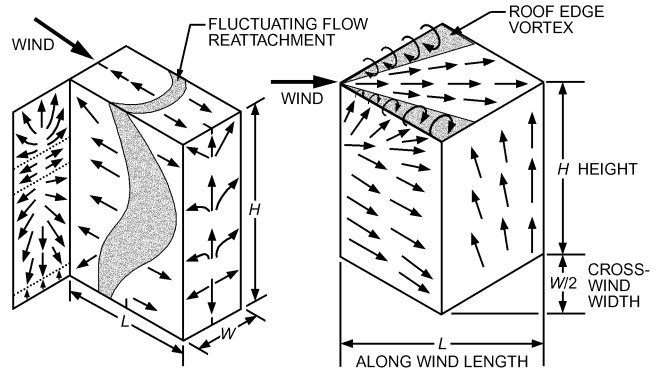
Fig. 5   Surface Flow Patterns and Building Dimensions

receptacles that create odors; trucks that serve the receptacles also produce odors. Air intakes should also not be placed near traffic or truck waiting areas. General building exhausts should also not be placed near outside contamination sources because flow reversal and ingestion of air through exhaust outlets can occur under some conditions (Seem et al. 1998).

Examining airflow around a building can help determine air intake placement. When wind is perpendicular to the upwind wall, air flows up and down the wall, dividing at about two-thirds up the wall (Figures 4 and 5). The downward flow creates ground-level swirl (shown in Figure 4) that stirs up dust and debris. To take advantage of the natural separation of wind over the upper and lower half of a building, toxic or nuisance exhausts should be located on the roof and intakes located on the lower one-third of the building, but high enough to avoid wind-blown dust, debris, and vehicle exhaust. If ground-level sources (e.g., wind-blown dust and vehicle exhaust) are major sources of contamination, rooftop intake is desirable.

Code Requirements for Air Intakes

Many model building codes exist, and local governments adopt and amend codes as needed. Architects and building systems designers need to be familiar with local and national codes applicable to each project. Mechanical and plumbing codes typically give minimum required separation distances for some situations. However, maintaining these separation distances does not necessarily guarantee that intake contamination will not occur.

One example of a model building code is the *Uniform Mechanical Code* (UMC) (IAPMO 1997a), which has been widely adopted in the United States. The UMC requires that exhausts be at least 3 ft from property lines and 3 ft from openings into buildings. Makeup air intakes should be placed to avoid recirculation. Grease and explosives-bearing ducts, combustion vents, and refrigeration equipment have special requirements: intakes should be at least 10 ft from combustion vents, plumbing vents, and exhaust air out-

lets, and be at least 10 ft above a road. Cooling towers should be 5 ft above or 20 ft away from intakes.

The *Uniform Plumbing Code* (UPC) (IAPMO 1997b), requires that exhaust vents from domestic water heaters be 3 ft or more above air inlets. Sanitary vents must be 10 ft or more from or 3 ft above air intakes. When UPC and UMC requirements conflict, the UPC provisions govern. However, local jurisdictions may modify codes, so the adopted versions may have significantly different requirements than the model codes.

Treatment and Control Strategies

When available intake/exhaust separation does not provide the desired dilution factor, or intakes must be placed in undesirable locations, ventilation air requires some degree of treatment, as discussed in Section 6.1.1 of ASHRAE *Standard* 62.1. Fibrous media, inertial collectors, and electrostatic air cleaners, if properly selected, installed, and maintained, can effectively treat airborne particles. Reducing gaseous pollutants requires scrubbing, absorptive, adsorptive, or incinerating techniques. Biological hazards require special methods such as using high-efficiency particulate air (HEPA) filters and ultraviolet light. Chapters 24 and 25 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment* describe these treatments in detail. One control approach that should be used with care is selective operation of intakes. If a sensor in the intake airstream detects an unacceptable level of some substance, the outside air dampers are closed until the condition passes. This strategy has been used for helicopter landing pads at hospitals and during emergency generator testing. The drawbacks are that pressurization is lost and ventilation air is not provided unless the recirculated air is heavily treated. In areas of chronically poor outside air quality, such as large urban areas with stagnant air, extensive and typically costly treatment of recirculated air may be the only effective option when outside air dampers are closed for extended periods.

Intake Locations for Heat-Rejection Devices

Cooling towers and similar heat-rejection devices are very sensitive to airflow around buildings. This equipment is frequently roof-mounted, with equipment intakes close to the roof where air can be considerably hotter and at a higher wet-bulb temperature than air that is not affected by the roof. This can reduce the capacity of cooling towers and air-cooled condensers.

Heat exchangers often take in air on one side and discharge heated, moist air horizontally from the other side. Obstructions immediately adjacent to these horizontal-flow cooling towers can drastically reduce equipment performance by reducing airflow. Exhaust-to-intake recirculation can be a serious problem for equipment that has an intake and exhaust on the same housing. Recirculation is even more serious than reduction in airflow rate for these devices. Recirculation of warm, moist exhaust raises the inlet wet-bulb temperature, which reduces performance. Recirculation can be caused by adverse wind direction, local disturbance of the airflow by an upwind obstruction, or by a close downwind obstruction. Vertical exhaust ducts may need to be extended to reduce recirculation and improve equipment effectiveness.

Wind Recirculation Zones on Flat-Roofed Buildings

Stack height design must begin by considering the wind recirculation regions (Figure 6). To avoid exhaust reentry, the stack plume must avoid rooftop air intakes and wind recirculation regions on the roof and in the wake downwind of the building. Where stacks or exhaust vents discharge within this region, gases rapidly diffuse to the roof and may enter ventilation intakes or other openings. Figures 4 and 6 show that exhaust gas from an improperly designed stack is entrained into the recirculating flow zone behind the downwind face and is brought back into contact with the building.
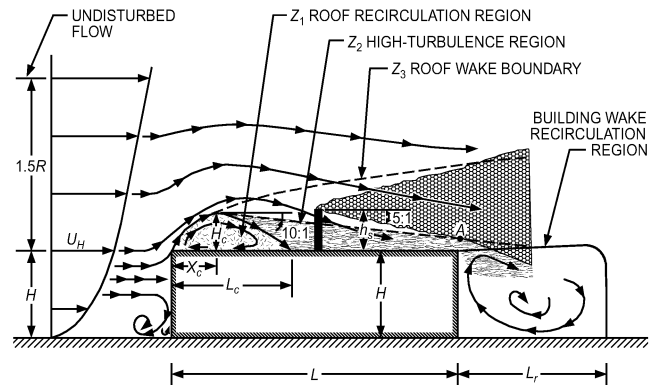
Fig. 6   Design Procedure for Required Stack Height to Avoid Contamination
(Wilson 1979)

Wilson (1979) found that, for a flat-roofed building, the upwind roof edge recirculation region height H_c at location X_c and its recirculation length L_c (shown in Figures 1 and 6) are proportional to the building size scale R:

$$H_c = 0.22R \qquad (1)$$

$$X_c = 0.5R \qquad (2)$$

$$L_c = 0.9R \qquad (3)$$

and the wind recirculation cavity length L_r on the downwind side of the building is approximately

$$L_r = R \qquad (4)$$

where R is the building scaling length:

$$R = B_s^{0.67} B_L^{0.33} \qquad (5)$$

where B_s is the smaller of the building upwind face dimensions (height or width) and B_L is the larger. These equations are approximate but are recommended for use. The dimensions of flow recirculating zones depend on the amount of turbulence in the approaching wind. High levels of turbulence from upwind obstacles can decrease the coefficients in Equations (1) to (4) by up to a factor of two. Turbulence in the recirculation region and in the approaching wind also causes considerable fluctuation in the position of flow reattachment locations (Figures 5 and 6).

Rooftop obstacles such as penthouses, equipment housings, and architectural screens are accounted for in stack design by calculating the scale length R for each of these rooftop obstacles from Equation (5) using the upwind face dimensions of the obstacle. The recirculation regions for each obstacle are then calculated from Equations (1) to (4). When a rooftop obstacle is close to the upwind edge of a roof or another obstacle, the flow recirculation zones interact. Wilson (1979) gives methods for dealing with these situations.

Building-generated turbulence is confined to the roof wake region, whose upper boundary Z_3 in Figure 6 is

$$Z_3/R = 0.28(x/R)^{0.33} \qquad (6)$$

where x is the distance from the upwind roof edge where the recirculation region forms. Building-generated turbulence decreases with increasing height above roof level. At the edge of rooftop wake boundary Z_3, turbulence intensity is close to the background level in the approach wind. The high levels of turbulence in the air below the

boundary Z_2 in Figure 6 rapidly diffuse exhaust gases downward to contaminate roof-level intakes. As shown in Figure 6, the boundary Z_2 of this high-turbulence region downwind of a wind recirculation region is approximated by a straight line sloping at 10:1 downward from the top of the wind recirculation zone to the roof. The stack in Figure 6 may be inadequate because at point A the plume intersects the high turbulence boundary Z_2. The geometric method for stack height is discussed in more detail in the next section.

GEOMETRIC METHOD FOR ESTIMATING STACK HEIGHT

This section presents a method of specifying stack height h_s so that the lower edge of the exhaust plume lies above air intakes and wind recirculation zones on the roof and downwind of the emitting building, based on flow visualization studies (Wilson 1979). This method does not calculate exhaust dilution in the plume; instead, it estimates the size of recirculation and high turbulence zones, and the stack height to avoid contamination is calculated from the shape of the exhaust plume. High vertical exhaust velocity is accounted for with a plume rise calculation that shifts the plume upward. Low vertical exhaust velocity that allows stack wake downwash of the plume (see Figure 3) is accounted for by reducing the effective stack height.

This stack height should prevent reentry of exhaust gas into the emitting building most of the time, provided no large buildings, structures, or terrain are nearby to disturb the approaching wind. The geometric method considers only intakes on the emitting building. Additional stack height or an exhaust-to-intake roof-level dilution calculation is often required if the exhaust plume can impinge on a nearby building (Wilson et al. 1998b). Dilution calculations should be used if this method produces an unsatisfactorily high stack, or if exhaust gases are highly toxic releases from fume hood exhaust.

Rooftop obstacles can significantly alter dispersion from exhaust stacks immediately downwind of the obstacles and of similar height to the obstacles (Saathoff et al. 2002). The goal of the geometric stack method is to ensure that the exhaust plume is well above the recirculation zones associated with these obstacles.

Step 1. Use Equations (1) to (5) to calculate the height and location of flow recirculation zones 1 and 2 and the recirculation zone downwind of the building (see Figure 6). All zones associated with rooftop obstacles up- and downwind of the stack location should be included. Note that zone 3 is not used in the geometric design method.

Step 2. Draw the recirculation regions on the top and downwind sides of penthouses, equipment housings, architectural screens, and other rooftop obstacles up- and downwind of the stack location. If there are intakes on the downwind wall of the building, include the building recirculation region L_r on this wall. Now, calculate the height h_{sc} of a stack with a rain cap (i.e., no plume rise), draw a line sloping down at 1:5 in the wind direction above the roof. Slide this line down toward the building as shown in Figure 1 until it contacts any one of the recirculation zones on any obstacle up- or downwind of the stack (or until the line contacts any portion of the building if there are no rooftop zones or sidewall intakes). With the line in this position, its height at the stack location is the smallest allowable plume height h_{sc} for that wind direction. Repeat for other wind directions to find the worst-case (highest) required plume height.

This estimated h_{sc} is based on an assumption that the plume spreads up and down from h_{sc} with a 1:5 slope (11.3°), as shown in Figure 6. (This slope represents a downward spread of approximately two standard deviations of a bell-curve Gaussian plume concentration distribution in the vertical direction.)

Step 3. Reduce the stack height to give credit for plume rise from uncapped stacks. Only jet momentum rise is used; buoyancy rise is considered as a safety factor. For an uncapped stack of diameter d_e, plume rise h_r from the vertical jet momentum of the exhaust is estimated from Briggs (1984) as

$$h_r = 3.0\beta d_e(V_e/U_H) \tag{7}$$

where

$$d_e = \sqrt{4A_e/\pi} \tag{8}$$

For an uncapped stack, the capping factor is $\beta = 1.0$. For a capped stack, $\beta = 0$, so $h_r = 0$, and no credit is given for plume rise. U_H is the maximum design wind speed at roof height for which air intake contamination must be avoided. This maximum design speed must be at least as large as the hourly wind speed exceeded 1% of the time. This 1% design speed is listed for many cities in Chapter 28 of the 2005 *ASHRAE Handbook—Fundamentals.* For cities not on this list, set U_H equal to 2.5 times the annual average hourly wind speed as recommended in Table 2 of Chapter 16 of the 2005 *ASHRAE Handbook—Fundamentals*.

The plume rise of Equation (7) is a final plume height that occurs some distance downwind. In reality, the plume gradually rises until reaching this height. Accounting for gradual plume rise is beyond the scope of this chapter. The plume rise of Equation (7) plus the physical stack height should not be considered equivalent to an effective stack height. A real stack of that height has better performance for two reasons: the effective height is achieved immediately instead of somewhere downstream, and the plume is higher than the effective height because of exhaust momentum. Stack height plus plume rise are additive in the geometric method as a simplification, but there are other conservatisms built into the geometric method to offset this approach.

Step 4. Increase stack height, if necessary, to account for stack wake downwash caused by low exhaust velocity, as described in the section on Recommended Stack Exhaust Velocity. For a vertically directed jet from an uncapped stack ($\beta = 1.0$), Wilson et al. (1998b) recommend a stack wake downwash adjustment h_d of

$$h_d = d_e(3.0 - \beta V_e/U_H) \tag{9}$$

for $V_e/U_H < 3.0$. For $V_e/U_H > 3.0$, there is no downwash and $h_d = 0$. Rain caps and louvers are frequently used on stacks of gas- and oil-fired furnaces and packaged ventilation units, for which $\beta = 0$ and $h_d = 3.0d_e$.

The final adjusted stack height h_s recommended is

$$h_s = h_{sc} - h_r + h_d \tag{10}$$

The advantage of using an uncapped stack instead of a capped stack is considerable. If the minimum recommended exhaust velocity V_e of $1.5U_H$ is maintained for an uncapped stack ($\beta = 1.0$), plume downwash $h_d = 1.5d_e$ and $h_r = 4.5d_e$. For a capped stack ($\beta = 0$), $h_d = 3.0d_e$ and $h_r = 0$. Using these values in Equation (10), an uncapped stack can be made $6.0d_e$ shorter than a capped stack.

Example 1. The stack height h_s of the uncapped vertical exhaust on the building in Figure 1 must be specified to avoid excessive contamination of intakes A and B by stack gases. The stack has a diameter d_e of 1.64 ft and an exhaust velocity V_e of 1770 fpm. It is located 52.5 ft from the upwind edge of the roof. The penthouse's upwind wall (with intake A) is located 98.4 ft from the upwind edge of the roof, 13.1 ft high, and 23.0 ft long in the wind direction. The top of intake A is 6.56 ft below the penthouse roof. The building has a height H of 49.2 ft and a length of 203 ft. The top of intake B is 19.7 ft below roof level. The width (measured into the page) of the building is 164 ft, and the penthouse is 29.5 ft wide. The annual average hourly wind speed is 7.95 mph at a nearby airport with an anemometer height H_{met} of 32.8 ft. The building is in suburban terrain (Category 2 in Table 1 of Chapter 16 of the 2005 *ASHRAE Handbook—Fundamentals*). Calculate the required stack height h_s by the geometrical method using the lowest allowable design wind speed.

Solution: The first step is to set the height h_{sc} of a capped stack by projecting lines with 1:5 slopes so that recirculation zones are covered, as shown in Figure 1. The only influence of intake location is that the

downwind recirculation zone must be considered if there is an intake on the downwind wall, which is true for intake B in this example.

First, check the rooftop recirculation zone associated with the penthouse. To find the height of this recirculation zone, use Equation (5):

$$R = (13.1)^{0.67}(29.5)^{0.33} = 17.1 \text{ ft}$$

Then use Equations (1) and (2):

$$H_c = (0.22)(17.1) = 3.76 \text{ ft}$$

$$X_c = (0.5)(17.1) = 8.55 \text{ ft}$$

With the 1:5 slope of the lower plume boundary shown in Figure 6, the capped stack height in Figure 1 (measured from the main roof) must be

$$h_{sc} = 0.2(98.4 - 52.5 + 8.55) + 3.76 + 13.1 = 27.8 \text{ ft}$$

to avoid the recirculation zone above the penthouse.

Next, check the building wake recirculation zone downwind of the building. The plume must also avoid this region because intake B is located there. The length of this recirculation region is found using Equation (4):

$$L_r = (49.2)^{0.67}(164)^{0.33} = 73.2 \text{ ft}$$

Projecting the downwind corner of this recirculation region upwind with a 1:5 slope to the stack location gives the required height of a no-downwash capped stack above the main roof level as

$$h_{sc} = 0.2(203 + 73.2 - 52.5) = 44.7 \text{ ft}$$

for the plume to avoid the recirculation zone on the downwind side of the building.

The design stack height is set by the condition of avoiding contamination of the building wake, because avoiding the penthouse roof recirculation requires only a 27.8 ft capped stack. Credit for plume rise h_r from the uncapped stack requires calculation of the building wind speed U_H at $H = 49.2$ ft. The minimum allowable design wind speed is the speed that is exceeded 1% of the time at the meteorological station. From Table 2 in Chapter 16 of the 2005 *ASHRAE Handbook—Fundamentals*, this is found by multiplying the hourly average wind speed by a factor of 2.5. In this case, for $H_{met} = 32.8$ ft at the airport meteorological station, this 1% wind speed is $U_{met} = 2.5(7.95) = 19.9$ mph = 1751 fpm. With the airport in open terrain (Category 3 of Table 1 of Chapter 16 of the 2005 *ASHRAE Handbook—Fundamentals*), and the building in urban terrain (Category 2), the wind speed adjustment parameters are $a_{met} = 0.14$ and $\delta_{met} = 900$ ft at the airport, and $a = 0.22$ and $\delta = 1200$ ft at the building. Using Equation (4) in Chapter 16 of the 2005 *ASHRAE Handbook—Fundamentals*, with building height $H = 49.2$ ft,

$$U_H = 1751\left(\frac{900}{32.8}\right)^{0.14}\left(\frac{49.2}{1200}\right)^{0.22} = 1379 \text{ fpm}$$

Because $V_e/U_H = 1770/1379 = 1.28$ is less than 3.0, there is some plume downwash as shown in Figure 3. From Equation (9),

$$h_d = 1.64[3 - 1.0(1.28)] = 2.8 \text{ ft}$$

Then, using Equation (7), the plume rise at design wind speed is

$$h_r = 3.0(1.64)(1.28) = 6.3 \text{ ft}$$

Using these values in Equation (10), the uncapped height h_{sc} is, with the height reduction credit for the 6.3 ft rise and the height addition to account for the 2.8 ft downwash,

$$h_s = 44.7 - 6.3 + 2.8 = 41.2 \text{ ft}$$

As shown in Figure 1, this stack height is measured above the main roof. If stack height is higher than desirable, an alternative is to use dilution calculations. The geometric method does not directly account for dilution within the plume.

EXHAUST-TO-INTAKE DILUTION CALCULATIONS

Worst-Case Critical Dilution

This section describes a method for computing outside dilution of exhausts emitted from a rooftop stack. The resulting dilution can be converted to contaminant concentration for comparison to odor thresholds or health limits. The results and equations given were obtained from wind tunnel studies of simple building shapes.

Dispersion of pollutants from building exhaust depends on the combined effect of atmospheric turbulence in the wind approaching the building and turbulence generated by the building itself. This building-generated turbulence is most intense in and near the flow recirculation zones that occur on the upwind edges of the building (Figures 1 and 5). Dilution of exhaust gas is estimated using design procedures developed for tall isolated stacks (EPA 1995), with modifications to include the high turbulence levels experienced by a plume diffusing over a building roof in an urban area. Halitsky (1982), Hosker (1984), Meroney (1982), and Wilson and Britter (1982) review gas diffusion near buildings.

The geometric stack design procedure does not give a quantitative estimate of the worst-case critical dilution factor D_{crit} at an air intake. If a required dilution can be specified with known stack emissions and required health limits, odor thresholds, or air quality regulations, computing critical dilutions can be an alternative for specifying stack heights. Petersen and Ratcliff (1991) and Smeaton et al. (1991) discuss use of emission information and formulation of dilution requirements in more detail. Exhaust from a single-source dedicated stack may require more atmospheric dilution than a single stack with the same exhausts combined because emissions are diluted in the exhaust manifold.

Dilution and Concentration Definitions

A building exhaust system releases a mixture of building air and pollutant gas at concentration C_e (mass of pollutant per volume of air) into the atmosphere through a stack or vent on the building. The exhaust mixes with atmospheric air to produce a pollutant concentration C, which may contaminate an air intake or receptor if the concentration is larger than some specified allowable value C_{allow} (see Figure 4). The dilution factor D between source and receptor mass concentrations is defined as

$$D = C_e/C \qquad (11)$$

where

C_e = contaminant mass concentration in exhaust, lb/ft^3
C = contaminant mass concentration at receptor, lb/ft^3

The dilution increases with distance from the source, starting from its initial value of unity. If C is replaced by C_{allow} in Equation (11), the atmospheric dilution D_{req} required to meet the allowable concentration at the intake (receptor) is

$$D_{req} = C_e/C_{allow} \qquad (12)$$

The exhaust (source) concentration is given by

$$C_e = \dot{m}/Q_e = \dot{m}/(A_e V_e) \qquad (13)$$

where

$\dot{m}$ = contaminant mass release rate, lb/s
$Q_e = A_e V_e$ = total exhaust volumetric flow rate, ft^3/s
A_e = exhaust face area, ft^2
V_e = exhaust face velocity, ft/s

The concentration units of mass per mixture volume are appropriate for gaseous pollutants, aerosols, dusts, and vapors. The concentration of gaseous pollutants is usually stated as a volume fraction f (contaminant volume/mixture volume), or as ppm (parts per million) if the volume fraction is multiplied by 10^6. The pollutant volume fraction f_e in the exhaust is

$$f_e = Q/Q_e \qquad (14)$$

where Q is the volumetric release rate of the contaminant gas. Both Q and Q_e are calculated at exhaust temperature T_e.

The volume concentration dilution factor D_v is

$$D_v = f_e / f \qquad (15)$$

where f is the contaminant volume fraction at the receptor. If the exhaust gas mixture has a relative molecular mass close to that of air, D_v may be calculated from the mass concentration dilution D by

$$D_v = (T_e / T_a) D \qquad (16)$$

where

    T_e = exhaust air absolute temperature, °R
    T_a = outside ambient air absolute temperature, °R

Many building exhausts are close enough to ambient temperature that volume fraction and mass concentration dilutions D_v and D are equal.

Gaussian Plume Equations for Roof-Level Dilution

This section presents equations for predicting worst-case roof-level dilution of exhaust from a vertical stack on a roof. The equations assume a bell-shaped Gaussian concentration profile in both the vertical and cross-wind horizontal directions. Gaussian profiles have been used in many atmospheric dispersion models, such as those used by the U.S. Environmental Protection Agency. Considering their simplicity, bell-shaped Gaussian concentration profiles in the cross-wind y and vertical z directions at a given horizontal distance x represent atmospheric dispersion remarkably well (Brown et al. 1993).

The dilution equations predict the roof-level dilution D_r, which is the ratio of contaminant concentration C_e at the exit point of the exhaust to the maximum concentration C_r on the plume centerline at roof level, giving $D_r = C_e / C_r$. The centerline of the plume is defined in the x direction, with y the lateral (cross-wind) distance off the plume centerline (axis), and z the vertical. Dilution is affected by three processes:

- Wind carries the plume downwind. The higher the wind speed, the greater the dilution on the plume axis. Wind speed U_H carrying the plume is the wind speed in the undisturbed flow approaching the top of the building.
- Wind turbulence spreads the plume vertically and laterally (crosswind). Plume spreads in the cross-wind y direction and the vertical z direction are σ_y and σ_z. These plume spreads increase with downwind distance.
- The plume is carried vertically by the initial buoyancy and vertical momentum of the exhaust at the stack exit. The higher the plume, the greater the dilution at the roof surface. The stronger the wind, the less the plume rises, which may produce less dilution.

Thus, wind speed has two influences: (1) at very low wind speed, the exhaust jet from an uncapped stack rises high above roof level, producing a large exhaust dilution D_r at a given intake location; and (2) at high wind speed, the dilution is also large because of longitudinal stretching of the plume by the wind. Between these extremes is the critical wind speed $U_{H,crit}$, at which the smallest amount of dilution occurs for a given exhaust and intake location.

Before performing Gaussian dilution calculations on a rooftop, the effect of rooftop obstacles, wind recirculation zones, and intake location(s) must be considered. Dilution depends on the vertical separation ζ between the plume centerline h_{plume} and h_{top}, defined as the highest of the intake, all active obstacles (discussed later), and recirculation zones defined in Equation (1). Vertical separation ζ is defined as

$$\zeta = h_{plume} - h_{top}$$
$$= 0 \text{ if } h_{plume} < h_{top} \qquad (17)$$

Plume centerline h_{plume} is defined as

$$h_{plume} = h_s + h_r - h_d \qquad (18)$$

where h_s is the physical stack height above the roof, h_r is the plume rise defined in Equation (7), and h_d is the stack wake downwash defined in Equation (9) (see Figure 1). Close to the stack, the value of ζ must be limited to avoid overprediction of the dilution, as discussed in the section on Limiting Contribution of Plume Rise to D_r Near Stacks.

To determine which rooftop obstacles are considered active in defining h_{top}, start by drawing a line in plan view through the stack location and the intake of interest. All obstacles along this line or one obstacle width laterally (y-direction) from the line are considered active. Obstacles and recirculation zones upstream of the stack and downstream of the intake should also be considered. The value of h_{top} is the higher of the active obstacles, recirculation zones (including zones on top of active obstacles) defined in Equation (1), and the height of the intakes. All of these heights should be referenced to the same roof level used to determine h_s. Once h_{top} is defined and ζ is calculated, dilution at the intake is calculated from

$$D_r = 4 \frac{U_H}{V_e} \times \frac{\sigma_y}{d_e} \times \frac{\sigma_z}{d_e} \exp\left(\frac{\zeta^2}{2\sigma_z^2}\right) \qquad (19)$$

When plume height is less than the height of intakes, active obstacles, and recirculation zones (i.e., $h_{plume} < h_{top}$), then $\zeta = 0$ and dilution should be calculated using Equation (23).

If exhaust gases are hot, buoyancy increases the rise of the exhaust gas mixture and produces lower concentrations (higher dilutions) at roof level. For all exhausts except very hot flue gases from combustion appliances, it is recommended that plume rise from buoyancy be neglected in dilution calculations and stack design on buildings. By neglecting buoyant plume rise, the predicted dilution has an inherent safety factor, particularly at low wind speed, where buoyancy rise is significant.

Limiting Contribution of Plume Rise to D_r Near Stacks

Close to the stack, the ratio $\zeta^2 / 2\sigma_z^2$ in Equation (19) becomes very large, causing the exponential term to overpredict roof-level dilution D_r. Preventing this requires that $\zeta^2 / 2\sigma_z^2$ not be allowed to exceed 7.0. Maintaining $\zeta^2 / 2\sigma_z^2 < 7.0$ limits the amount of dilution allowed by plume rise to $\exp(7.0) = 1100$ near the stack. Limiting $\zeta^2 / 2\sigma_z^2$ to 7.0 means $\zeta = 3.74\sigma_z$. In effect, this limits Equation (19) to an effective plume height no more than 3.74 vertical plume standard deviations σ_z above the $h_s = 0$ plane.

Cross-Wind and Vertical Plume Spreads for Dilution Calculations

Equations for vertical and cross-wind spread were developed for nonbuoyant exhaust jets from rooftop stacks on flat-roofed buildings (Wilson et al. 1998a). In the first 1000 ft downwind from the stack, both cross-wind plume spread σ_y and vertical plume spread σ_z increase almost linearly with distance X. The recommended equations for plume spreads are based on full-scale atmospheric measurements by McElroy and Pooler (1968) in an urban area, as used in the EPA (1995) model ISCST. The urban ISCST equations are adjusted here from the 60 min measured averaging time to 2 min averages with the 0.2 power law applied to both vertical and crosswind spreads. Then, the vertical spread over a building roof is assumed to remain constant at the 2 min averaging time value for longer averaging times. The plume equations are as follows:

$$\frac{\sigma_y}{d_e} = 0.071 \left(\frac{t_{avg}}{2.0}\right)^{0.2} \frac{X}{d_e} + \frac{\sigma_o}{d_e} \qquad (20)$$

$$\frac{\sigma_z}{d_e} = 0.071\frac{X}{d_e} + \frac{\sigma_o}{d_e} \qquad (21)$$

where t_{avg} is the concentration averaging time in minutes, X is the distance downwind from the stack, and σ_o is the initial source size that accounts for stack diameter and for dilution jet entrainment during plume rise.

The dependence of initial spread σ_o on exit velocity to wind speed ratio V_e/U_H is

$$\frac{\sigma_o}{d_e} = \left[0.125\beta\frac{V_e}{U_H} + 0.911\beta\left(\frac{V_e}{U_H}\right)^2 + 0.250\right]^{0.5} \qquad (22)$$

where β is the rain cap factor: $\beta = 1$ for no rain cap, and $\beta = 0$ if there is a rain cap. For $\beta = 0$, there is still an effective source size σ_o equal to half the diameter d_e of the stack.

The averaging time over which exhaust gas concentration exposures are measured is important in determining roof-level dilution. As averaging time increases, the exhaust gas plume meanders more from side to side, reducing the time-averaged concentration (and increasing the dilution) observed at an air intake location. The effect of changing the averaging time over a range of about 2 to 180 min can be estimated by adjusting the 2 min value of the cross-wind spread σ_y by the 0.2 power of the averaging time t_{avg} (Wollenweber and Panofsky 1989). This averaging time adjustment appears directly in Equation (20). If the exhaust and intake are both located in the same flow recirculation region, dilution is less sensitive to averaging time than predicted by the 0.2 power law. For the case of both stack tip and air intake in the same wind recirculation zone, assume the D_r values for 2 min averages also apply for all averaging times from 2 to 60 min.

Equations (17), (18), (19), and (20) imply that dilution does not depend on the location of either the exhaust or intake, only on the horizontal distance X between them and the vertical separation ζ. This is reasonable when both exhaust and intake locations are on the same building wall or on the roof. Dilution can increase if the intake is below roof level on the sidewall of a building and the exhaust stack is located on the roof; however, at present there are no reliable estimates for this effect on stack exhaust.

Stack Design Using Dilution Calculations and Charts for Critical Wind Speed

Starting with the volume flow rate Q_e and exit diameter d_e of an exhaust stack, dilution calculations can be used to select the design stack height h_s required to produce a specified minimum exhaust-to-intake criteria dilution D at horizontal distance X from the stack. First, the exhaust velocity at the stack tip is calculated from $Q_e = \pi V_e d_e^2/4$. Next, an initial stack height h_s above the roof is selected. Determining final stack height is a trial-and-error procedure in which a first guess is made for the stack height and dilution is calculated for several wind speeds to determine the worst-case critical wind speed $U_{H,crit}$ at which the minimum dilution D_{crit} occurs. Starting with a high U_H (e.g., the speed exceeded less than 1% of the time), a spreadsheet is used to calculate the plume rise h_r from Equation (7), downwash h_d from Equation (9), and plume spreads σ_o, σ_y, and σ_z from Equations (20), (21), and (22). Using the first guess for stack height h_s, Equation (18) is used to calculate plume height h_{plume}. Next, h_{top} is determined and Equation (17) used to calculate the vertical separation ζ. If $\zeta > 0$, Equation (19) is used to calculate the roof-level dilution at the air intake; otherwise, Equation (23) is used. Note that when $\zeta^2/2\sigma_z^2$ is calculated, it must be limited to a maximum of 7.0 in Equation (19). D_r is then recalculated for a range of U_H to determine the critical wind speed at which minimum dilution D_{crit} occurs. If D_{crit} is too high or too low, h_s is

adjusted and the dilution calculations repeated to find a new critical wind speed and dilution.

The charts for four different heights of uncapped stacks (Figure 7) can be used to speed up calculation of h_s. To use the charts, h_s should be referenced above an actual or fictitious h_{top} (i.e., when final h_s is determined from the charts, it is added to h_{top} to determine the final stack height above the roof). Once an initial h_s is selected, the ratios of stack height to inside diameter (h_s/d_e) and of the exhaust-to-intake distance to stack height (X/h_s) are calculated. The two charts with h_s/d_e ratios higher and lower than this first guess are used to read up to the lowest V_e/U_H curve at that X/h_s to find the minimum dilution D_{crit} and critical exhaust velocity ratio $V_e/U_{H,crit}$. Linear interpolation using h_s/d_e between values from the two charts is used to find the D_{crit} and $V_e/U_{H,crit}$ for the first-guess stack height. If this critical dilution is too low or too high, the stack height is adjusted for the second guess and the procedure is repeated until the desired stack height is found.

Figure 8 is a design chart for dilution from capped stacks ($\beta = 0$) with no plume rise. For capped stacks, the critical wind speed for minimum dilution at an intake is related to increased plume spread observed at low wind speeds rather than the competing effects of plume rise versus wind dilution. After making a first guess for stack height, the minimum critical dilution for capped stacks can be calculated directly using the a value $U_{H,crit} = 400$ fpm. This is based on the observation that, for wind speeds less than 400 fpm at roof height, the atmosphere tends to develop high levels of turbulence that cause plume meandering and increase exhaust-to-intake dilution.

Example 2. Using the same building geometry as in Example 1, calculate the dilution for a shorter stack with $h_s = 27.9$ ft above the main roof. The stack has a diameter d_e of 1.64 ft and an exhaust velocity V_e of 1770 fpm. The stack gas concentration must be diluted by 1800:1 to be considered safe for 2 min exposures at intakes A and B. (This required dilution is determined from occupational health standards and estimated emission rates.) Using the dilution charts, calculate the critical roof-level dilution factor D_{crit} and critical wind speed $U_{H,crit}$ for contamination for intakes A and B. Is the stack height of 27.9 ft sufficient to handle this toxic substance?

Solution:

Intake A. In this example, intake A is some height above the main rooftop on the side of the penthouse. There are no recirculation zones or obstructions between the stack and the intake. The penthouse is 13.1 ft above the roof and downwind of the stack, and the peak of the building recirculation zone is upwind of the stack. Thus, $h_{top} = 13.1$ ft. For intake A with this configuration, it is recommended to use the portion of h_s above h_{top} when using the charts: $27.9 - 13.1 = 14.8$ ft. The horizontal distance from the stack to the intake is $X = 45.9$ ft. The stack height ratio is $h_s/d_e = 14.8/1.64 = 9.0$, and the exhaust-to-intake distance ratio $X/h_s = 45.9/14.8 = 3.10$. Then, using Figure 7C for $h_s/d_e = 10$, the critical minimum dilution is 3000, at a critical exhaust velocity to wind speed ratio of about 0.5. Repeating this using Figure 7B for $h_s/d_e = 5$ yields a critical dilution of 250 and a critical exhaust velocity to wind speed ratio of 0.5. Then, interpolating linearly on the height ratio h_s/d_e,

$$D_{crit} = 3000 - \frac{(10 - 9.0)}{(10 - 5)}(3000 - 250) = 2450$$

Because D_{crit} occurred at $V_e/U_H = 0.5$ on both charts, no interpolation is required and $V_e/U_{H,crit} = 0.5$.

From this velocity ratio, the critical wind speed at roof height is $U_{H,crit} = 1770/0.5 = 2240$ fpm (25.4 mph) for intake A. This high wind speed is likely to occur very rarely. (In Example 1, the hourly average wind speed $U_H = 1379$ fpm or 15.7 mph is exceeded only 1% of the time.) With a predicted dilution of 2450:1, the dilution target of 1800:1 is met at intake A.

Intake B. For intake B, the penthouse for intake A now lies downwind of the stack and upwind of the intake. From Example 1, the recirculation zone on top of the penthouse is 3.8 ft tall. For this example, h_{top} is equal to the height of this penthouse recirculation zone above the roof: $h_{top} = 13.1 + 3.8 = 16.9$ ft. Thus, to use the charts, the height h_s

A. $h_s/d_e = 2.5$

B. $h_s/d_e = 5$

C. $h_s/d_e = 10$

D. $h_s/d_e = 20$

| $V_e/U_H = 8.0$ | $V_e/U_H = 6.0$ | $V_e/U_H = 4.0$ | $V_e/U_H = 2.0$ |
| $V_e/U_H = 1.0$ | $V_e/U_H = 0.5$ | $V_e/U_H = 3.0$ | |
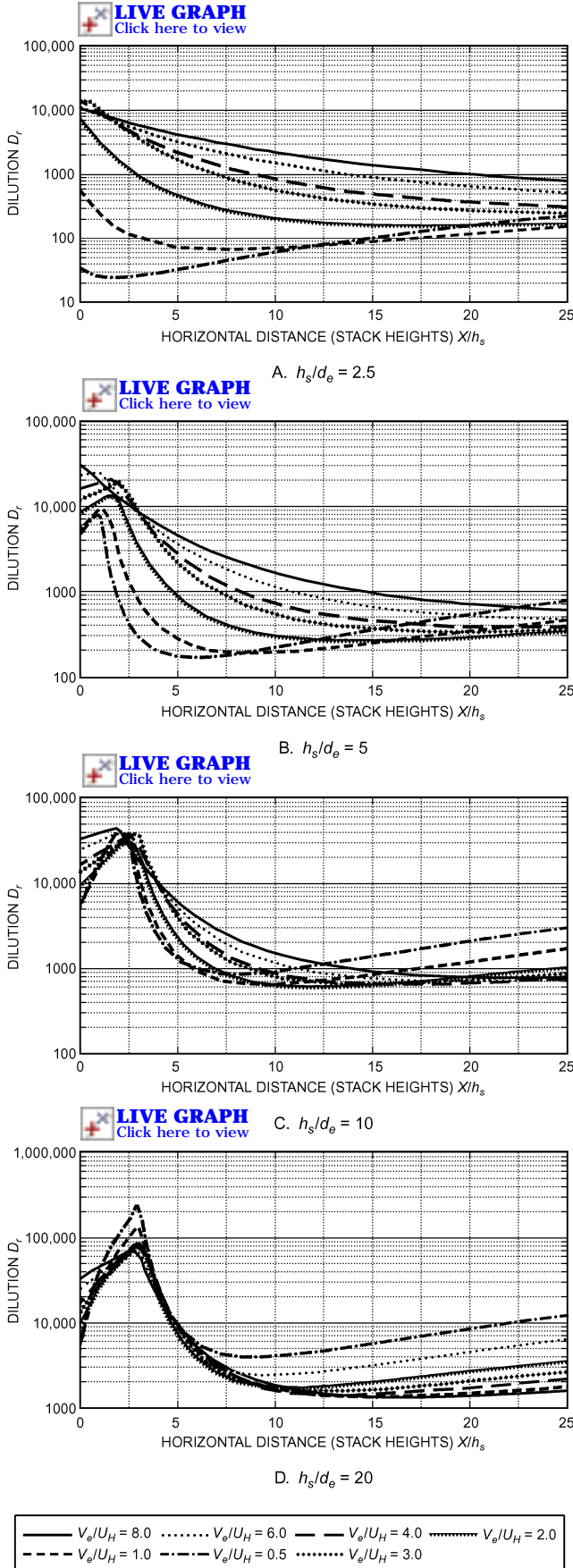
Fig. 7   Dilution Versus Distance for Uncapped Stacks

| $h_s/d_e = 20$ | $h_s/d_e = 10$ | $h_s/d_e = 5$ | $h_s/d_e = 2.5$ |
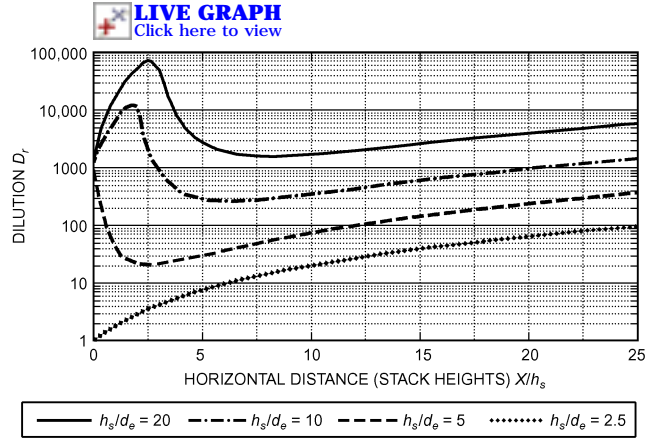
Fig. 8   Dilution Versus Distance for Capped Stack

above h_{top} must be used: $h_s = 27.9 - 16.9 = 11$ ft.   The horizontal distance from stack to intake is $X = 150.3$ ft. Then, the stack height ratio is $h_s/d_e = 11/1.64 = 6.7$, and the exhaust-to-intake distance ratio $X/h_s = 150.3/11 = 13.7$. Then, using Figure 7C for $h_s/d_e = 10$, the critical minimum dilution is 600, at a critical exhaust velocity to wind speed ratio of about 2.0. Repeating this using Figure 7B for $h_s/d_e = 5$ yields a critical dilution of 230 and a critical exhaust velocity to wind speed ratio of 1.0. Then, interpolating linearly on the height ratio h_s/d_e,

$$D_{crit} = 600 - \frac{(10 - 6.7)}{(10 - 5)}(600 - 230) = 356$$

$$\frac{V_e}{U_{H,crit}} = 2 - \frac{(10 - 6.7)}{(10 - 5)}(2 - 1.0) = 1.3$$

From this velocity ratio the critical wind speed at roof height is $U_{H,crit} = 1770/1.3 = 1362$ fpm (15.5 mph) for intake B. As with intake A, this speed occurs less than 1% of the time.

In summary, intake A with a critical dilution of 2450 met the health and safety requirement of providing a minimum exhaust-to-intake dilution of at least 1800, whereas intake B with a dilution of 356:1 did not.

Dilution from Flush Exhaust Vents with No Stack

For exhaust grilles and louvers on the roof or walls of a building or penthouse, vertical separation $\zeta = 0$ in Equation (19). Combining Equations (19), (20), and (21) gives

$$D_s = 4\frac{U_H}{V_e}\left[0.071\left(\frac{t_{avg}}{2.0}\right)^{0.2}\frac{S}{d_e} + \frac{\sigma_o}{d_e}\right]\left(0.071\frac{S}{d_e} + \frac{\sigma_o}{d_e}\right) \qquad (23)$$

where the stretched-string distance S between the nearest edge of the exhaust to the nearest edge of the intake replaces horizontal distance X in the cross-wind and vertical plume spreads σ_y and σ_z in Equations (20) and (21). The concentration averaging time t_{avg} at the intake is in minutes, for the reference averaging time of 2.0 min. The subscript s in the dilution D_s from a surface exhaust distinguishes it from the roof-level dilution D_r from a stack [Equation (19)]. The initial dilution in the flush-vent exhaust plume can be approximated by an uncapped jet with $\beta = 1.0$ in Equation (22) to calculate the effective source spread σ_o that generates the self-dilution by jet entrainment.

Minimum critical dilutions for flush exhausts can be calculated using the approximate value $U_{H,crit} = 400$ fpm based on the observation that, for wind speeds less than 400 fpm at roof height, the atmosphere tends to develop high levels of turbulence that increase exhaust-to-intake dilution. For flush roof exhausts with no stack, and for wall intakes, the experiments of Li and Meroney (1983) suggest that D_s at the intake is about a factor of 4 larger than the dilution at a roof-level intake the same stretched-string distance S from the stack.

Example 3. The exhaust flow of Q_e = 3740 cfm in Example 1 comes from a louvered grille at location A. The exhaust grille is 2.3 ft high and 2.3 ft wide. What is the critical exhaust-to-intake dilution factor at intake B on the downwind wall of the building for averaging times of 2 min and 60 min?

Solution: Exhaust grille A has a face area of A_e = 5.29 ft^2 and an exhaust velocity V_e of 707 fpm. From Equation (8), the effective exhaust diameter is d_e = [(4)(5.29)/π]$^{0.5}$ = 2.60 ft. The stretched-string distance S from exhaust A to intake B is the sum of the 6.56 ft from the top of A to the top of the penthouse, plus the 23 ft length of the penthouse, plus the sloped line of horizontal length 81.6 ft from the downwind edge of the penthouse roof, and a vertical drop of 13.1 ft to the roof, plus the 19.7 ft to intake B:

$$S = 6.56 + 23.0 + \sqrt{81.6^2 + (13.1 + 19.7)^2} = 117.5 \text{ ft}$$

so that S/d_e = 117.5/2.60 = 45.2 ft. The critical wind speed is approximately $U_{H,crit}$ = 400 fpm for capped stacks and flush vents. The initial plume spread σ_o is calculated from Equation (22) with V_e/U_H = 707/400 = 1.77 ft, and an uncapped exhaust, β =1.0,

$$\frac{\sigma_o}{d_e} = \sqrt{0.125(1.0)(1.77) + 0.911(1.0)(1.77)^2 + 0.250} = 1.82$$

The critical dilution of exhaust from A at intake B is calculated from Equation (23):

$$D_{s,crit} = 4\left(\frac{400}{707}\right)\left[0.071\left(\frac{t_{avg}}{2.0}\right)^{0.2}(45.2) + 1.82\right][0.071(45.2) + (1.82)]$$

For an averaging time t_{avg} = 2 min, the critical dilution is 57, and 93 for a 60 min averaging time. Because the plume from A passes around the edge of the roof to reach intake B, dilution can be increased by a factor of 4 (Li and Meroney 1983) to obtain $D_{s,crit}$ = 57(4) = 228 for 2 min and $D_{s,crit}$ = 93(4) = 372 for 60 min. These are conservative estimates because they represent the dilution at a low critical wind speed of 400 fpm, which is 4.5 mph. Using the method in Example 1, the annual average hourly wind speed at roof height is 6.3 mph.

Annual Hours of Occurrence of Highest Intake Contamination

To assess the severity of the hazard caused by intake contamination, it is useful to know the number of hours per year that exhaust-to-intake dilution is likely to be no more than a factor of two higher than the worst-case minimum dilution D_{crit} calculated at $U_{H,crit}$. The first step in making a frequency-of-occurrence estimate for the number of low-dilution hours is to use the dilution charts in Figures 7 and 8 to find the range of wind speeds U_H over which the dilution D_r is within a factor of two of D_{crit}. The upper and lower limits of this range are then converted to the upper and lower limits of the meteorological station wind speed U_{met}. Weather data are then used to calculate the number of hours per year that wind speeds fall in this range. This number of hours is multiplied by the fraction of time the local wind direction lies in a sector 22.5° on each side of the line joining the exhaust and intake location.

Combined Exhausts and Ganged Stacks

When exhaust from several collecting stations is combined in a single vent or in a tight cluster of stacks (as recommended in the section on Exhaust Stack and Air Intake Design Strategies), the exhaust concentration C_e of each contaminant stream decreases by mixing with other exhaust streams, and the plume rise increases due to the higher mass flow in the combined jet. Combined exhaust streams significantly lower roof-level intake concentration C_r compared to that from separate exhausts. Where possible, exhausts should be combined before release to take advantage of this increase in overall dilution.

Influence of Architectural Screens on Exhaust Dilution

Architectural screens are often placed around rooftop equipment to reduce noise or hide equipment. Unfortunately, these screens interact with windflow patterns on the roof and can adversely affect exhaust dilution and thermal efficiency of equipment inside the screen. This section describes a method to account for these screens by modifying the physical stack height h. Architectural screens generate flow recirculation regions similar to those shown downwind of the building and penthouse in Figure 1. These screens are often made of porous materials with mesh or louvers, which influence the height of the recirculation cavity above the screens.

To incorporate the effect of architectural screens into existing dilution prediction equations, a stack height reduction factor F_h is introduced. Using the equation developed by Petersen et al. (1999), stack height h_s above the roof must be multiplied by F_h when the stack is enclosed within a screen. Effective stack height $h_{s,eff}$ measured above roof level is

$$h_{s,eff} = F_h h_s \tag{24}$$

The stack height reduction factor F_h is directly related to screen porosity P_s. For stack heights above the top of the screen that are less than 2.5 times the height of the screen,

$$F_h = 0.81 P_s + 0.20 \tag{25}$$

where porosity is

$$P_s = \frac{\text{Open area}}{\text{Total area}} \tag{26}$$

F_h is applied directly to h_s after the required stack height has been calculated, and should be included where the physical stack height is less than 2.5 times the height of the architectural screen.

Example 4. Calculate the required stack height for an uncapped stack with a height of 15.5 ft above roof level, surrounded by a 10 ft high, 50% porous architectural screen.

Solution: To determine the effect of the 50% porous screen, use Equation (25) with P_s = 0.5

$$F_h = 0.81(0.5) + 0.2 = 0.605$$

The screen has reduced the effective stack height from its actual height of 15.5 ft to

$$h_{s,eff} = 0.605(15.5) = 9.38 \text{ ft}$$

When the effect of the 50% porous screen is added, the 15.5 ft stack height is found to behave like a 9.38 ft stack. The actual stack height h_s must be increased to account for the screen's effect. This is most easily done by dividing h_s by the stack height reduction factor:

$$h_{s,corrected} = \frac{h_s}{F_h} = \frac{15.5}{0.605} = 25.6 \text{ ft}$$

The corrected 25.6 ft high stack effectively behaves like a 15.5 ft tall stack, and should produce the same dilution at downwind air intakes.

Scale Model Simulation and Testing

For many routine design applications, exhaust dilution can be estimated using the data and equations presented in this chapter, which are based on scale modeling of simple building shapes. However, in critical applications, such as where health and safety or energy costs are of concern, or for complicated building configurations, physical modeling or full-scale field evaluations may be required to obtain more accurate estimates. Measurements on small-scale models in wind tunnels or water channels can provide the required design information. Scale modeling is discussed in Chapter 16 of the 2005 *ASHRAE Handbook—Fundamentals*.

SYMBOLS

A_e = stack or exhaust exit face area, ft^2

B_L = larger of two upwind building face dimensions H and W, ft

B_s = smaller of two upwind building face dimensions H and W, ft

C = contaminant mass concentration at receptor at ambient air temperature T_e, Equation (11), lb/ft^3

C_{allow} = allowable concentration of contaminant at receptor, Equation (12)

C_e = contaminant mass concentration in exhaust at exhaust temperature T_e, Equation (11), lb/ft^3

D = dilution factor between source and receptor mass concentrations, Equation (11)

D_{crit} = critical dilution factor at roof level for uncapped vertical exhaust at critical wind speed $U_{H,crit}$ that produces smallest value of D_r for given exhaust-to-intake distance S and stack height h_s

d_e = effective exhaust stack diameter, Equation (8), ft

D_r = roof-level dilution factor D at given wind speed for all exhaust locations at same fixed distance S from intake, Equation (19)

D_{req} = atmospheric dilution required to meet allowable concentration of contaminant C_{allow}, Equation (12)

D_S = dilution at a wall or roof intake from a flush exhaust grille or louvered exhaust, Equation (23)

D_v = dilution factor between source and receptor using volume fraction concentrations, Equation (15)

f = contaminant volume concentration fraction at receptor; ratio of contaminant gas volume to total mixture volume, Equation (15), ppm × 10^{-6}

f_e = contaminant volume concentration fraction in exhaust gas; ratio of contaminant gas volume to total mixture volume, Equation (14), ppm × 10^{-6}

F_h = stack height adjustment factor to adjust existing stack height above screen for influence of screen of exhaust gas dilution, Equation (25)

H_c = maximum height above roof level of upwind roof edge flow recirculation zone, Equation (1), ft

h_{crit} = height of plume above roof level with plume rise and downwash calculated at the critical wind speed U_{crit}, ft

h_d = downwash correction to be subtracted from stack height, Equation (9), ft

H_{met} = anemometer height, ft

h_{plume} = final plume height, Equation (18), ft

h_r = plume rise of uncapped vertical exhaust jet, Equation (7), ft

h_s = physical exhaust stack height (typically above roof unless otherwise specified), ft

h_{sc} = required height of capped exhaust stack to avoid excessive intake contamination, Equation (10), ft

$h_{s,eff}$ = effective exhaust stack height above roof on which it is located, corrected for an architectural screen surrounding the stack, Equation (24), ft

h_{top} = height of highest of intake, active obstacle, or recirculation zone on a rooftop between the stack and intake, Equation (17), ft

L = length of building in wind direction, Figure 5, ft

L_c = length of upwind roof edge recirculation zone, Equation (3), ft

L_r = length of flow recirculation zone behind rooftop obstacle or building, Equation (4), ft

$\dot{m}$ = contaminant mass release rate, Equation (13), lb/s

P_s = porosity of an architectural screen near a stack, Equation (26)

Q = contaminant volumetric release rate, Equation (14), ft^3/s

Q_e = total exhaust volumetric flow rate, Equation (13), ft^3/s

R = scaling length for roof flow patterns, Equation (5), ft

S = stretched-string distance; shortest distance from exhaust to intake over obstacles and along building surface, Equation (23), ft

T_a = outdoor ambient air absolute temperature, Equation (16), °R

t_{avg} = time interval over which receptor (intake) concentrations are averaged in computing dilution, Equation (20), min

T_e = exhaust air mixture absolute temperature, Equation (16), °R

U_H = mean wind speed at height H of upwind wall in undisturbed flow approaching building, Equation (7), ft/s

$U_{H,crit}$ = critical wind speed that produces smallest roof-level dilution factor D_{crit} for uncapped vertical exhaust at given X and h_s, ft/s

V_e = exhaust gas velocity, Equation (13), ft/s

W = width of upwind building face, ft

x = horizontal distance from upwind roof edge where recirculation region forms in direction of wind, ft

X = downwind horizontal distance from center of stack, Equations (20) and (21), ft

X_c = distance from upwind roof edge to H_c, Equation (2), ft

y = cross-wind distance off the plume centerline, ft

z = vertical distance, ft

Z_1 = height of flow recirculation zone boundary above roof, Figure 6, ft

Z_2 = height of high turbulence zone boundary above roof, Figure 6, ft

Z_3 = height of roof edge wake boundary above the roof, Equation (6) and Figure 6, ft

Greek

β = capping factor; 1.0 for vertical uncapped roof exhaust; 0 for capped, louvered, or downward-facing exhaust

ζ = vertical separation above h_{top}, Equation (17), ft

σ_o = standard deviation of initial plume spread at the exhaust used to account for initial dilution, Equation (20), ft

σ_y = standard deviation of cross-wind plume spread, Equation (20), ft

σ_z = standard deviation of vertical plume spread, Equation (21), ft

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CHAPTER 45

CONTROL OF GASEOUS INDOOR AIR CONTAMINANTS

THE ONLY reason to remove a gaseous contaminant from an airstream is that it would otherwise have harmful or annoying effects on the ventilated space or its occupants. These effects are noticeable at different concentration levels for different contaminants. There are four categories of harmful effects: Toxicity, odor, irritation, and material damage. In most cases, contaminants become annoying through irritation or odor before they reach levels toxic to humans, but this is not always true. For example, the potentially deadly contaminant carbon monoxide has no odor.

Traditionally, indoor gaseous contaminants are controlled with ventilation air drawn from outdoors, but available outdoor air may contain undesirable gaseous contaminants at unacceptable concentrations. If so, it requires treatment by gaseous contaminant removal equipment before being used for ventilation. In addition, minimizing outdoor airflow by using a high recirculation rate and filtration is an attractive means of energy conservation. However, recirculated air cannot be made equivalent to fresh outdoor air by removing only particulate contaminants. Noxious, odorous, and toxic gaseous contaminants must also be removed by gaseous contaminant control equipment, which is frequently different from particulate filtration equipment.

This chapter covers design procedures for gaseous contaminant control for occupied spaces only. The procedures discussed in this chapter are appropriate to control odors and gaseous irritants. Control of contaminants for the express purpose of protecting building occupants (whether against deliberate attack or industrial accidents) or to protect artifacts (such as in museums) requires application of the same design principles, but applied more rigorously and with great emphasis on having specific design and performance data, providing redundancy, and added engineering safety factors. Design for protection is not a focus of this chapter, although published design guidance is included and referenced; for more detail, see Chapter 58. Aspects of air-cleaning design for museums, libraries, and archives are included in Chapter 21 of this volume, and control of gaseous contaminants from industrial processes and stack gases is covered in Chapter 25 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*.

TERMINOLOGY

The terminology used in control of gaseous air contaminants is specific to the field, and the meaning of some terms familiar from particle filtration is slightly different. In particular, gaseous contaminant technology performance is a function of (1) the specific contaminant, (2) its concentration, (3) airflow rate, and (4) environmental conditions. Several methods of measuring the performance of a gaseous control device, some unique to this application, are defined in the following.

Adsorption. Attraction of a sorbate to the surface, both outer surface and inner pore surface, of media by physical forces (Van der Waals forces).

Activity. Mass of sorbate contained in a sorbent at saturation, expressed as a percentage or fraction of the carbon mass (i.e., grams contaminant/grams adsorbent). Activity is an equilibrium property under particular challenge conditions, and is not a function of airflow. (In most cases, commercial sorbent bed filters are changed for efficiency reasons well before the sorbent is saturated.) If a saturated adsorbent bed is then exposed to clean air, some of the adsorbed contaminant will desorb. Activity is generally greater than retentivity.

Breakthrough. While removing gaseous contaminants from an airstream passing through a media bed, the point at which downstream contaminant concentration is measurable and begins to rise rapidly.

Breakthrough curve. Plot of contaminant penetration versus time.

Breakthrough time. Operating time (at constant operating conditions) before a certain penetration is achieved. For instance, the 10% breakthrough time is the time between beginning to challenge an adsorber and the time at which air discharged contains 10% of the contaminant feed concentration. Continued operation leads to 50% and eventually to 100% breakthrough, at which point a physical adsorbent is saturated. For a chemisorber, the media is exhausted. (Some commercial devices are designed to allow some of the challenge gas to bypass the sorbent. These devices break through immediately, and breakthrough time, as defined here, does not apply.)

Catalyst. Any substance of which a small proportion notably affects the rate of a chemical reaction without itself being consumed or undergoing a chemical change. Most catalysts accelerate reactions, but a few retard them (negative catalysts, or inhibitors).

Channeling. Disproportionate or uneven flow of fluid (gas or liquid) through passages of lower resistance, which can occur in fixed beds or columns of granular media because of nonuniform packing, irregular sizes and shapes of media, gas pockets, wall effects, and other causes.

Challenge. Airstream containing contaminant(s) of interest that is fed to the air cleaner.

Chemisorption (chemical adsorption). Binding a sorbate to the surface of a solid by forces with energy levels approximately those of a chemical bond.

Concentration. Quantity of one substance dispersed in a defined amount of another.

Density, apparent (bulk density). Mass under specified conditions of a unit volume of a solid sorbent, including its pore volume and interparticle voids.

Efficiency. (1 – Penetration); usually expressed as a percentage or decimal fraction.

Efficiency curve. Plot of contaminant removal efficiency against time for a particular challenge concentration and airflow.

HEPA. High-efficiency particle air filter.

The preparation of this chapter is assigned to TC 2.3, Gaseous Air Contaminants and Gas Contaminant Removal Equipment.

Mass transfer zone. Depth of adsorption media required to remove essentially all of an incoming contaminant; dependent on media, contaminant nature, contaminant inlet concentration, and environmental conditions.

Mean particle diameter. Weighted average particle size, in millimeters, of a granular adsorbent; computed by multiplying the percent retained in a size fraction by the respective mean sieve openings, summing these values, and dividing by 100.

Media. Granular or pelletized adsorbent (or chemisorbent) used in gaseous contaminant control equipment.

Penetration. Ratio of breakthrough (downstream) concentration to challenge (inlet) concentration, usually expressed as a percentage or decimal fraction. Unlike particulate filters, physical adsorbents and chemisorbents both decline in efficiency as they load. The decline can be very sudden, and is usually not linear with time.

Pressure drop. Difference in pressure between two points in an airflow system, caused by frictional resistance to airflow in a duct, filter, or other system component, or by a media bed or air-cleaning devices.

Removal efficiency. Measure of amount of challenge gas removed at a given time by physical and/or chemical means.

Residence time. Theoretical time period that contaminant molecule is within the boundaries of the media bed. The longer the residence time, the higher the efficiency, and the longer the bed life. For gaseous contaminant control equipment, residence time is computed as

$$\text{Residence time} = \frac{\text{Bed area exposed to airflow} \times \text{Bed depth}}{\text{Airflow rate}} \quad (1)$$

For commercial gaseous contaminant air cleaners, residence time computation neglects the fact that a significant fraction of the volume of the bed is occupied by the media. For example, a unitary adsorber containing trays totaling 40 ft^2 media in a 1 in. deep bed, challenged at 2000 cfm, has a residence time of 0.1 s. Given this definition, a deeper media bed, lower airflow rate, or adsorbers in series increase residence time and thus adsorber performance. Because gaseous contaminant air cleaners all tend to have approximately the same granule size and the same kind of activated carbon, residence time is a generally useful indicator of performance. In some engineering disciplines, the volume of the adsorbent media is subtracted from the nominal volume of packed beds when calculating residence time. This gives a shorter residence time value and is not normally used for HVAC.

Different ways of arranging the media, different media, or different media granule sizes all change the residence time. The geometry and packaging of some adsorbent technologies makes computation of residence time difficult. For example, the flow pattern in pleated fiber-carbon composite media is difficult to specify, making residence time computation uncertain. Therefore, although residence times can be computed for partial-bypass filters, fiber-adsorbent composite filters, or fiber-bonded filters, they cannot be compared directly and may serve more as a rating than as an actual residence time. Manufacturers might publish equivalent residence time values that say, in effect, that this adsorber performs the same as a traditional deep-bed adsorber, but no standard test exists to verify such a rating.

Retentivity. Amount of a particular adsorbate remaining in an adsorbant after a saturated bed reaches equilibrium in clean air, usually stated as a percentage or fraction of the sorbate mass. Retentivity represents the ability of an adsorbent to resist desorption of the adsorbate. Retentivity is generally less than activity.

Saturation. State of a physical adsorbent when it contains all the contaminant it can hold at the challenge concentration, temperature, and humidity.

Vapor-phase contaminant. Substance in gas form that naturally occurs as a solid or liquid at the temperature and pressure of the location where it is present.

VOCs. Volatile organic compounds.

GASEOUS CONTAMINANTS

Ambient air contains nearly constant amounts of nitrogen (78% by volume), oxygen (21%), and argon (0.9%), with varying amounts of carbon dioxide (about 0.03%) and water vapor (up to 3.5%). In addition, trace quantities of inert gases (neon, xenon, krypton, helium, etc.) are always present.

Gases other than these natural constituents of air are usually considered contaminants. Their concentrations are almost always small, but they may have serious effects on building occupants, construction materials, or contents. Removing these gaseous contaminants is often desirable or necessary.

Sources of nonindustrial contaminants are discussed in Chapter 12 in the 2005 *ASHRAE Handbook—Fundamentals*. However, for convenience, data on some of the contaminants in cigarette smoke (Table 1), and some contaminants emitted by building materials (Table 2), indoor combustion appliances (Table 3), and occupants (Table 4) are provided here.

Table 5 gives typical outdoor concentrations for gaseous contaminants at urban sites; however, these values may be exceeded if the building under consideration is located near a fossil fuel power plant, refinery, chemical production facility, sewage treatment plant, municipal refuse dump or incinerator, animal feed lot, or other major source of gaseous contaminants. If such sources have a significant influence on the intake air, a field survey or dispersion model must be run. Many computer programs have been developed to expedite such calculations.

Using Source Data to Predict Indoor Concentrations

Source data such as those in Tables 1 to 5 provide raw information on which control system designs can be based. Outdoor air contaminants enter buildings through the outdoor air intake and through infiltration. The indoor sources enter the occupied space air and are distributed through the ventilation system. If measurements are not available, source data can be used to predict the contaminant challenge to air-cleaning systems using building air quality models. The following relatively simple published model is intended as an introduction to the topic.

Meckler and Janssen (1988) described a model for calculating the effect of outdoor pollution on indoor air quality, which is outlined in this section. A recirculating air-handling schematic is shown schematically in Figure 1. In this case, mixing is not perfect; the horizontal dashed line represents the boundary of the region close to the ceiling through which air passes directly from the inlet diffuser to the return air intake. Ventilation effectiveness E_v is the fraction of total air supplied to the space that mixes with room air and does not

Table 1 Major Contaminants in Typical Cigarette Smoke

Contaminant	Weighted Mean ETS Generation Rate, μg/cigarette	Weighted Standard Error, μg/cigarette	Method
Carbon monoxide	55,101	1,064	Nondispersive IR
Ammonia	4,148	107	Cation exchange cartridge
Acetaldehyde	2,500	54	DNPH cartridge
Formaldehyde	1,330	34	
Summary VOC measurements			
Total HC by FID	27,810	83	FID
Total sorbed and IDed VOC	11,270		Sorbent tube/GC
Total sorbed VOC	1,907.1	525	Sorbent tube/GC
Respirable particles	13,674	411	Gravimetric

DNPH = 2,4-dinitrophenylhydrazine; IR = infrared; VOC = volatile organic compound; ETS = environmental tobacco smoke; FID = flame ionization detector; GC = gas chromatography.
Source: Martin et al. (1997).

bypass the room along the ceiling. Meckler and Janssen suggest a value of 0.8 for E_v. Any people in the space are additional sources and sinks for gaseous contaminants. In the ventilated space, the steady-state contaminant concentration results from the summation of all contaminants added to the space a divided by the total ventilation and amounts removed b. The steady-state concentration C_{ss} for a single component can be expressed as (Meckler and Janssen 1988)

$$C_{ss} = a/b \qquad (2)$$

where

$$a = C_x(Q_i + 0.01PE_vQ_v/f) + 0.5885(G_i + NG_O) \qquad (3)$$

$$b = Q_e + Q_h + Q_L + k_dA + NQ_O(1 - 0.01P_O) \\ + (E_vQ - Q_v)(1 - 0.01P)/f \qquad (4)$$

and

- A = surface area inside ventilated space on which contaminant can be adsorbed, ft^2
- C_{ss} = steady-state indoor concentration of contaminant, µg/m^3
- C_x = outdoor concentration of contaminant, µg/m^3
- E_v = ventilation effectiveness, fraction
- f = $1 - 0.01P(1 - E_v)$
- G_i = generation rate for contaminant by nonoccupant sources, µg/h
- G_O = generation rate for contaminant by an occupant, µg/h
- k_d = deposition velocity on a for contaminant, fpm
- N = number of occupants
- P = filter penetration for contaminant, %
- P_O = penetration of contaminant through human lung, %
- Q = total flow, cfm
- Q_e = exhaust airflow, cfm
- Q_h = hood flow, cfm
- Q_i = infiltration flow, cfm
- Q_L = leakage (exfiltration) flow, cfm
- Q_O = average respiratory flow for a single occupant, cfm
- Q_v = ventilation (makeup) airflow, cfm

Flow continuity allows the expression for b to be simplified, which may make it easier to determine flows:

$$b = Q_i + Q_v + k_dA + NQ_O(1 - 0.01P_O) \qquad (5)$$

The parameters for this model must be determined carefully so that nothing significant is ignored. Leakage flow Q_L, for example, may include flow up chimneys or toilet vents.

The steady-state concentration is of interest for design. It may also help to know how rapidly concentration changes when conditions change suddenly. The dynamic equation for the building in Figure 1 is

$$C_I = C_{ss} + (C_0 - C_{ss})e^{-b\theta/V} \qquad (6)$$

where

- V = volume of the ventilated space, ft^3
- C_0 = concentration in space at time $\theta = 0$
- C_I = concentration in space θ minutes after a change of conditions
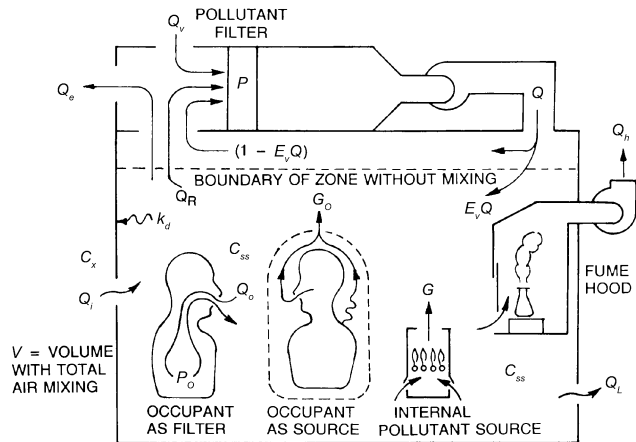
Fig. 1 Recirculatory Air-Handling and Gaseous Contaminant Schematic

Table 2 Example Generation of Gaseous Contaminants by Building Materials

	Average Generation Rate, µg/(h·m^2)						
Contaminant	Caulk	Adhesive	Linoleum	Carpet	Paint	Varnish	Lacquer
C-10 Alkane	1200						
n-Butanol	7300						760
n-Decane	6800						
Formaldehyde				44	150		
Limonene		190					
Nonane	250						
Toluene	20	750	110	160	150		310
Ethyl benzene	7300						
Trimethyl benzene		120					
Undecane						280	
Xylene	28						310

	Average Generation Rate, µg/(h·m^2)						
Contaminant	GF Insulation	GF Duct Liner	GF Duct Board	UF Insulation	Particle Board	Underlay	Printed Plywood
Acetone					40		
Benzene					6		
Benzaldehyde					14		
2-Butanone					2.5		
Formaldehyde	7	2	4	340	250	600	300
Hexanal					21		
2-Propanol				6			

GF = glass fiber; UF = ureaformaldehyde foam
Sources: Matthews et al. (1983, 1985), Nelms et al. (1986), and White et al. (1988).

Table 3 Example Generation of Gaseous Contaminants by Indoor Combustion Equipment

	Generation Rates, µg/Btu					Typical Heating Rate, 1000 Btu/h	Typical Use, hour/day	Vented or Unvented	Fuel
	CO_2	CO	NO_2	NO	HCHO				
Convective heater	53,500	88	13	18	1.45	31	4	U	Natural gas
Controlled-combustion wood stove		14	0.04	0.07		13	10	V	Oak, pine
Range oven		210	11	23		32	1.0*	U	Natural gas
Range-top burner		68	11	18	1.1	9.5/burner	1.7	U	Natural gas

*Sterling and Kobayashi (1981) found that gas ranges are used for supplemental heating by about 25% of users in older apartments. This increases the time of use per day to that of unvented convective heaters.
Sources: Cole (1983); Leaderer et al. (1987); Moschandreas and Relwani (1989); Sterling and Kobayashi (1981); Traynor et al. (1985); and Wade et al. (1975).

Table 4   Example Total-Body Emission of Some Gaseous Contaminants by Humans

Contaminant	Typical Emission, µg/h	Contaminant	Typical Emission, µg/h
Acetaldehyde	35	Methane	1,710
Acetone	475	Methanol	6
Ammonia	15,600	Methylene chloride	88
Benzene	16	Propane	1.3
2-Butanone (MEK)	9,700	Tetrachloroethane	1.4
Carbon dioxide	32×10^6	Tetrachloroethylene	1
Carbon monoxide	10,000	Toluene	23
Chloroform	3	1,1,1-Trichloroethane	42
Dioxane	0.4	Vinyl chloride monomer	0.4
Hydrogen sulfide	15	Xylene	0.003

Sources: Anthony and Thibodeau (1980); Brugnone et al. (1989); Cohen et al. (1971); Conkle et al. (1975); Gorban et al. (1964); Hunt and Williams (1977); and Nefedov et al. (1972).

Table 5   Typical Outdoor Concentration of Selected Gaseous Air Contaminants

Contaminants	Typical Concentration, ppbv	Contaminants	Typical Concentration, ppbv
Acetaldehyde	11	Methylene chloride	0.7
Acetone	1.3	Nitric acid	2.3
Ammonia	1.7	Nitric oxide	8.2
Benzene	2.5	Nitrogen dioxide	27
2-Butanone (MEK)	0.1	Ozone	20
Carbon dioxide	340,000*	Phenol	5.2
Carbon monoxide	2,600	Propane	10
Carbon disulfide	100	Sulfur dioxide	92
Carbon tetrachloride	0.3	Sulfuric acid	1.5
Chloroform	0.2	Tetrachloroethylene	0.4
Ethylene dichloride	2.5	Toluene	5.3
Formaldehyde	16	1,1,1-Trichloroethane	0.7
n-Heptane	7	Trichloroethylene	2.8
Mercury (vapor)	0.0006	Vinyl chloride	0.3
Methane	1,700	Xylene	2.3
Methyl chloride	4.4		

*Normal concentration of carbon dioxide in air. The concentration in occupied spaces should be maintained at no greater than three times this level (1000 ppmv).
Sources: Braman and Shelley (1980); Casserly and O'Hara (1987); Chan et al. (1990); Cohen et al. (1989); Coy (1987); Fung and Wright (1990); Hakov et al. (1987); Hartwell et al. (1985); Hollowell et al. (1982); Lonnemann et al. (1974); McGrath and Stele (1987); Nelson et al. (1987); Sandalls and Penkett (1977); Shah and Singh (1988); Singh et al. (1981); Wallace et al. (1983); and Weschler and Shields (1989).

C_{ss} is given by Equation (2), and *b* by Equation (5), with the parameters for the new condition inserted.

Reducing air infiltration, leakage, and ventilation air to reduce energy consumption raises concerns about indoor contaminant build-up. A low-leakage structure may be simulated by letting $Q_i = Q_L = Q_h = 0$. Then

$$C_{ss} = \frac{\dfrac{0.01 P E_v Q_v C_x}{f} + 2119(G_i + N G_O)}{Q_e + K_d A + N Q_O(1 - 0.01 P_O) + \dfrac{(E_v Q - Q_v)(1 - 0.01 P)}{f}} \quad (7)$$

Even if ventilation airflow $Q_v = 0$, a low-penetration (high-efficiency) gaseous contaminant filter and a high recirculation rate help lower the internal contaminant concentration. In commercial structures, infiltration and exfiltration are never zero. The only inhabited spaces operating on 100% recirculated air are space capsules,

undersea structures, and structures with life-support to eliminate carbon dioxide and carbon monoxide and supply oxygen.

Real buildings generally have many rooms, with multiple and varying sources of gaseous contaminants and complex room-to-room air changes. In addition, mechanisms other than adsorption may eliminate gaseous contaminants on building interior surfaces. Nazaroff and Cass (1986) provide estimates for contaminant deposition velocity k_d in Equations (2) to (5) that range from 0.0006 to 0.12 fpm for surface adsorption only. A worst-case analysis, yielding the highest estimate of indoor concentration, is obtained by setting $k_d = 0$. Nazaroff and Cass (1986) and Sparks (1988) describe computer programs to handle these calculations. Details on multizone modeling can be found in Chapter 34 of the 2005 *ASHRAE Handbook—Fundamentals*.

The assumption of bypass and mixing used in the models presented here approximates the multiple-room case, because gaseous contaminants are readily dispersed by airflows. Also, a gaseous contaminant diffuses from a zone of high concentration to one of low concentration, even with low rates of turbulent mixing.

Quantities appropriate for the flows in Equations (2) to (7) are discussed in the sections on Local Source Control and Dilution Through General Ventilation. Infiltration flow can be determined approximately by the techniques described in Chapter 27 of the 2005 *ASHRAE Handbook—Fundamentals* or, for existing buildings, by tracer or blower-door measurements. ASTM *Standard* E741 defines procedures for tracer-decay measurements. Tracer and blower-door techniques are given in ASTM (1980); DeFrees and Amberger (1987) describe a variation on the blower-door technique useful for large structures.

PROBLEM ASSESSMENT

Consensus design criteria (allowable upper limit of C_{ss} for any contaminant) do not exist for most nontoxic chemicals. Chapter 9 of the 2005 *ASHRAE Handbook—Fundamentals* discusses health effects of gaseous contaminants and provides some guidance on acceptable indoor concentrations, and Chapter 12 of that volume discusses the nature and non-health-related effects of gaseous contaminants, as well as providing some guidance on assessment.

Ideally, design for control of gaseous contaminants is based on accurate knowledge of the identity and concentration (as a function of time) of the contaminants to be controlled. This knowledge may come from estimates of source strength and modeling or direct measurement, or from direct measurements of the contaminants. Unfortunately, definitive assessment is seldom possible, so often careful observation, experience, and judgment must supplement data as the basis for design.

Two general cases exist: (1) new ventilation systems in new buildings for which contaminant loads must be estimated or measured, and (2) modification of existing ventilation systems to solve particular problems. For the first case, models such as described previously must be used. Identify contaminant-generating activities, estimate and sum the building sources, and identify outside air contaminants. Gaps in contaminant load data must be filled with estimates or measurements. Once contaminants and loads are identified, design can begin.

For control of a particular problem, measurements may also be required to identify the contaminant. Assessing the problem can become an indoor air quality investigation, including building inspection, occupant questionnaires, and local sampling and analysis. The *Building Air Quality Guide* (EPA 1991) is useful for such investigations. Again, once the contaminants and loads are understood, design can begin.

Contaminant Load Estimates

Valuable guidance on estimating contaminant loads in industrial situations is given by Burton (2003). In the 2005 *ASHRAE*

Handbook—Fundamentals, Chapter 12 discusses sampling and measurement techniques for industrial and nonindustrial environments, and Chapter 13 covers evaluating odor levels.

Results of sampling and analysis identify contaminants and their concentrations at particular places and times or over known times. Several measurements, which may overlap or have gaps in the contaminants analyzed and times of measurement, are usually used to estimate the overall contaminant load. Measurements are used to develop a time-dependent estimate of contamination in the building, either formally through material balance or informally through experience with similar buildings and contamination. The degree of formality applied depends on the severity of potential health or corrosion effects.

CONTROL STRATEGIES

Four control strategies may be used to improve the indoor air quality in a building: (1) elimination of sources, (2) local hooding with exhaust or recirculated air cleaning, (3) dilution with increased general ventilation, and (4) general ventilation air cleaning with or without increased ventilation rates. Usually, the first three are favored because of cost considerations. Control by general air cleaning is difficult because it is applied after the contaminants are fully dispersed and at their lowest concentration.

Elimination of Sources

This strategy is the most effective and often the least expensive. For instance, prohibiting smoking in a building or isolating it to limited areas greatly reduces indoor pollution, even when rules are poorly enforced (Elliott and Rowe 1975; Lee et al. 1986). Control of radon gas begins with installing traps in sewage drains and sealing and venting leaky foundations and crawlspaces (EPA 1986, 1987). Using waterborne materials instead of those requiring organic solvents may reduce VOCs, although Girman et al. (1984) show that the reverse is sometimes true. Substituting carbon dioxide for halocarbons in spray-can propellants is an example of using a relatively innocuous contaminant instead of a more troublesome one. Growth of mildew and other organisms that emit odorous contaminants can be restrained by controlling condensation and applying fungicides and bactericides, provided they are registered for the use and carefully chosen to have low off-gassing potential.

Local Source Control

Local source control is more effective than control by general ventilation when discrete sources in a building generate substantial amounts of gaseous contaminants. If these contaminants are toxic, irritating, or strongly odorous, local control and outdoor exhaust is essential. Bathrooms and kitchens are the most common examples. Some office equipment benefits from direct exhaust. Exhaust rates are sometimes set by local codes. The minimum transport velocity required for capturing large particles differs from that required for gaseous contaminants; otherwise, the problems of capture are the same for both gases and particles.

Hoods are normally provided with exhaust fans and stacks that vent to the outdoors. Hoods need large quantities of tempered makeup air, which requires a great deal of fan energy, so hoods waste heating and cooling energy. Makeup for air exhausted by a hood should be supplied so that the general ventilation balance is not upset when a hood exhaust fan is turned on. Back diffusion from an open hood to the general work space can be eliminated by surrounding the work space near the hood with an isolation enclosure, which not only isolates the contaminants, but also keeps unnecessary personnel out of the area. Glass walls for the enclosure decrease the claustrophobic effect of working in a small space.

Increasingly, codes require filtration of hood exhausts to prevent toxic releases to the outdoors. Hoods should be equipped with controls that decrease their flow when maximum protection is not needed. Hoods are sometimes arranged to exhaust air back into the occupied space, saving heating and cooling that air. This practice must be limited to hoods exhausting the most innocuous contaminants because of the risk of filter failure. Design and operation of effective hoods are described in *Industrial Ventilation: A Manual of Recommended Practice* (ACGIH 2004), and in Chapter 30 of this volume.

Dilution Through General Ventilation

In residential and commercial buildings, the chief use of local source control and hooding occurs in kitchens, bathrooms, and occasionally around specific point sources such as diazo printers. Where there is no local control of contaminants, the general ventilation distribution system provides contaminant control through dilution. These systems must meet both thermal load requirements and contaminant control standards. Complete mixing and a relatively uniform air supply per occupant are desirable for both purposes. The air distribution guidelines in Chapters 33 and 35 of the 2005 *ASHRAE Handbook—Fundamentals* are appropriate for contamination control by general ventilation. Airflows set by ASHRAE *Standard* 62.1 must be met.

When local exhaust is combined with general ventilation, a proper supply of makeup air must equal the exhaust flow for any hoods present. Supply fans may be needed to provide enough pressure to maintain flow balance. Clean spaces are designed so that static pressure forces air to flow from cleaner to less clean spaces, and the effects of doors opening and wind pressure, etc., dictate the need for backdraft dampers. Chapter 16 covers clean spaces in detail.

CONTROL BY VENTILATION AIR CLEANING

If eliminating sources, local hooding, or dilution cannot control contaminants, or are only partially effective, the air must be cleaned. Designing such a system requires understanding of the capabilities and limitations of control processes.

Design goals are discussed at greater length in the section on Air Cleaner System Design, but it is appropriate to mention at this point that complete and permanent removal of every contaminant is often not necessary. Intermittent nuisance odors, for instance, can often be controlled satisfactorily and economically using a design that "shaves the peak" to below the odor threshold and then slowly releases the contaminant back into the air, still below the odor threshold. On the other hand, such an approach would be inappropriate for a contaminant that affected occupants' health.

Gas Contaminant Control Processes

Many chemical and physical processes remove gases or vapors from air, but those of commercial interest to the HVAC engineer are physical adsorption and chemisorption. The operational parameters of greatest interest are removal efficiency, pressure drop, operational lifetime, first cost, and operating and maintenance cost. Other processes currently have extremely limited application in HVAC work, and are only briefly discussed.

Physical Adsorption. Adsorption is a surface phenomenon similar in many ways to condensation. Contaminant gas molecules strike a surface and remain bound to it (adsorbed) for an appreciable time. Surfaces of gaseous contamination control adsorption media are expanded in two ways to enhance adsorption. First, the media are provided in granular, pelletized, or fibrous form to increase the gross surface exposed to an airstream. Second, the media's surface is treated to develop microscopic pores, greatly increasing the area available for molecular contact. Typical activated alumina has a surface area of 1 to 1.6×10^6 ft^2 per pound; typical activated carbon has a surface area from 4 to 8×10^6 ft^2/lb. Pores of various microscopic sizes and shapes form minute traps that can fill with condensed contaminant molecules.
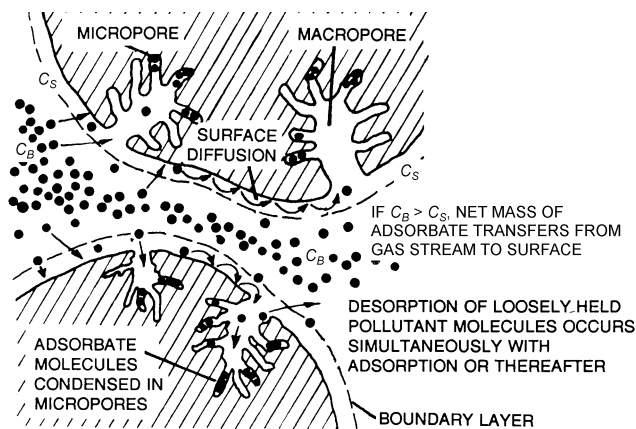
Fig. 2   **Steps in Contaminant Adsorption**

Fig. 3   **Dependence of Contaminant Concentration
on Bed Depth and Exposure Time**

The most common adsorbent granules are millimeter-sized, and the granules are used in the form of packed beds. In general, packed beds composed of larger monodispersed particles have lower pressure drops per unit depth of sorbent than those composed of smaller monodispersed particles. On the other hand, more adsorbent can be packed in a given volume with smaller particles, and that adsorbent is more accessible to the contaminant, but the pressure drop is higher at a fixed bed depth.

Several steps must occur in adsorption of a molecule (Figure 2):

1. The molecule is transported from the carrier gas stream across the boundary layer surrounding the adsorbent granule. This occurs randomly, with molecular movement both to and from the surface; the net flow of molecules is toward the surface when the concentration of contaminant in the gas flow is greater than at the granule surface. For this reason, adsorption decreases as contaminant load on the adsorbent surface increases. Very low concentrations in the gas flow also result in low adsorption rates.
2. The molecules of the contaminant diffuse into the pores to occupy that portion of the surface. Diffusion distances are lower and adsorption rates higher for smaller particles of adsorbent.
3. The contaminant molecules are bound to the surface. (Sorption is exothermic, releasing energy. At the low concentrations and sorption rates generally found in HVAC applications, sorbents operate nearly isothermally.)

Any of these steps may determine the rate at which adsorption occurs. In general, step 3 is very fast for physical adsorption, but reversible: adsorbed molecules can be desorbed later, either when cleaner air passes through the adsorber bed or when another contaminant arrives that either binds more tightly to the adsorber surface or is present at a much higher concentration. Complete desorption usually requires adding thermal energy to the bed.

When a contaminant is fed at constant concentration and constant gas flow rate to an adsorber of sufficient bed depth L, the gas stream concentration within the bed varies with time θ and bed depth, as shown in Figure 3A. When bed loading begins ($\theta = 0$), the contaminant concentration decreases logarithmically with bed depth; deeper into the bed, the slope of the concentration-versus-bed depth curve flattens at a very low value. Later, the entrance of the adsorber bed becomes loaded with contaminant, so contaminant concentrations in the gas stream are higher at each bed depth.

Distribution of contaminant in an adsorber bed is often described in terms of an idealized **mass transfer zone (MTZ)**. Conceptually, all contaminant adsorption takes place in the MTZ. Upstream, the adsorbent is spent and the concentration is equal to the inlet concentration. Downstream, all contaminant has been adsorbed and the concentration is zero. The movement of the MTZ through the media
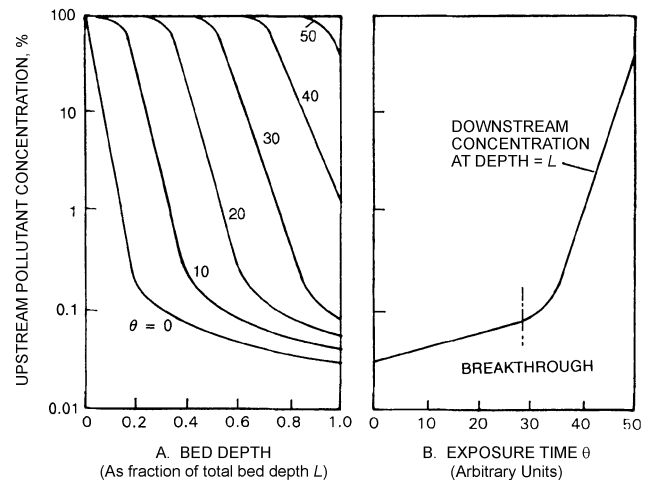
bed is known as the **adsorption wave**. Though in actuality the front and back of the zone are not sharply defined, for many media/contaminant combinations the MTZ provides a very useful picture of media performance.

For the same constant contaminant feed, the pattern of downstream concentration versus time for an adsorber of bed depth L is shown in Figure 3B. Usually, downstream concentration is very low until breakthrough time θ_{BT}, when the concentration rises rapidly until downstream concentration is the same as upstream. The logarithmic scale makes the downstream concentration appear higher than it is. At the breakthrough point, the downstream concentration is at less than 0.1% of the upstream, just as the slope of the curve increases. For purposes of defining the MTZ, choosing this point is reasonable. For protection purposes, any contaminant downstream might be too much; for nuisance odors, staying below the odor threshold might be adequate. The interval between these various breakthrough times could be very short or significant, depending on contaminant and media. However, not all adsorber/contaminant combinations show as sharp a breakthrough as in Figure 3B.

Multiple contaminants produce more complicated penetration patterns: individually, each contaminant might behave as shown in Figure 3B, but each has its own time scale. The better-adsorbing contaminants are captured in the upstream part of the bed, and the poorer are adsorbed further downstream. As the challenge continues, the better-adsorbing compound progressively displaces the other until the displaced component can leave the adsorber bed at a higher concentration than it entered.

Underhill et al. (1988) and Yoon and Nelson (1988) discuss the effect of relative humidity on physical adsorption. Water vapor acts as a second contaminant, altering adsorption parameters by reducing the amount of the first contaminant that can be held by the adsorber and shortening breakthrough times. For solvent-soluble VOCs adsorbed on carbon, relative humidity's effect is modest up to about 50%, and greater at higher percentages. On the other hand, chemicals that dissolve in water may experience increased sorption into the water layer at high relative humidities.

Chemisorption. The three physical adsorption steps also apply to chemisorption. However, the third step in chemisorption is by chemical reaction with electron exchange between the contaminant molecule and the chemisorber. This action differs in the following ways from physical adsorption:

- Chemisorption is highly specific; only certain contaminant compounds will react with a particular chemisorbent.
- Chemisorption is generally not reversible. Once the adsorbed contaminant has reacted, it is not desorbed. However, one or more

reaction products, different from the original contaminant, may be formed in the process, and these reaction products may enter the air as a new contaminant.

- Water vapor often helps chemisorption or is necessary for it, whereas it usually hinders physical adsorption.
- Chemisorption per se is a monomolecular layer phenomenon; the pore-filling effect that takes place in physical adsorption does not occur, except where adsorbed water condensed in the pores forms a reactive liquid.

Most chemisorptive media are formed by coating or impregnating a highly porous, nonreactive substrate (e.g., activated alumina, zeolite, or carbon) with a chemical reactant. The reactant will eventually become exhausted, but the substrate may have physical adsorption ability that remains active when chemisorption ceases.

Other Processes. Physical adsorption and chemisorption are the most commonly used processes, but the following processes are used in some applications.

Liquid absorption devices (scrubbers) and **combustion devices** are used to clean exhaust stack gases and process gas effluent. They are not commonly applied to indoor air cleanup. Additional information may be found in Chapter 25 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*.

Catalysts can clean air by stimulating a chemical reaction on the surface of the media. **Catalytic combustion** or **catalytic oxidation (CatOx)** oxidizes moderate concentrations of unburned hydrocarbons in air. In general, the goal with catalytic oxidation is to achieve an adequate reaction rate (contaminant destruction rate) at ambient temperature. Reaction products are a concern, because oxidation of nonhydrocarbons or other reactions can produce undesirable byproducts. This technology has been used industrially for years, but its potential use for indoor air cleaning is relatively new. Equipped with custom catalysts and operated at elevated pressures and temperatures, CatOx can be extremely effective at the removal of indoor contaminants, but is not currently cost-competitive in commercial indoor air or HVAC applications. Availability of waste heat significantly improves CatOx cost competitiveness. CatOx systems have potential application in security and protection applications.

Photocatalysis uses light [usually ultraviolet (UV)] and a photocatalyst to perform **reduction-oxidation (redox)** chemistry on the catalyst's surface. The device admits reactant gas species, notably air contaminants, in a feed stream and emits product species. The photocatalyst can be granular, bulk, or unsupported, or it can be supported as a thin film on media such as glass, polymer, or metal. The light sources must emit photons of energy greater than that of the intrinsic band-gap energy (E_g) of the photocatalyst. For example, the photocatalyst titanium dioxide (TiO_2) has band-gap energy of 3.1 eV; ultraviolet light has sufficient energy to overcome the E_g of TiO_2. The characteristic chemistry consists of reactant gases adsorbing onto the photocatalyst, followed by reaction chemistry, product formation, and desorption. With appropriate irradiance and flow rate of the reactant species, photocatalysis can almost completely oxidize a wide variety of organic compounds such that the exit gas stream contains carbon dioxide and water.

At its current level of catalyst and lamp development, UV photocatalysis is not cost-competitive for indoor air control, but the technology is developing rapidly. It is attractive because of its promise of reduced maintenance (no filters to maintain and dispose of) and cost compared to conventional technology. ASHRAE Research Project RP-1134 exhaustively reviewed the literature on UV photocatalysis (Tompkins et al. 2005a, 2005b).

Biofiltration is effective for low concentrations of many VOCs found in buildings (Janni et al. 2001). It is suitable for exhaust air cleaning, and is used in a variety of applications, including plastics, paper, and agricultural industries and sewage treatment plants. Operating costs are low, and installation is cost-competitive. However, concerns over using uncharacterized mixtures of bacteria in the filter, possible downstream emissions of microbials or chemicals, and the risk of unexpected or undetected failure make it unsuitable for cleaning air circulated to people.

Ozone is often touted as a panacea for removing gas-phase contaminants from indoor air. However, considerable controversy surrounds its use in indoor air. Ozone is a criteria pollutant and its maximum allowable concentration [8 h time-weighted average (TWA)] is regulated in both indoor (OSHA 1994) and outdoor air (EPA 1997). Some ozone generators can quickly produce hazardous levels of ozone (Shaughnessy and Oatman 1991). Furthermore, the efficacy of ozone at low concentrations for removing gaseous pollutants has not been documented in the literature (Boeniger 1995). Human sensory results obtained in conjunction with a study by Nelson et al. (1993) showed that an ozone/negative ion generator used in a tobacco-smoke environment (1) produced unacceptable ozone levels at the manufacturer's recommended settings, and (2) when adjusted to produce acceptable ozone levels, produced more odor and eye irritation over time than environmental tobacco smoke (ETS). Other work by Nelson (unpublished) has shown the rapid oxidation of NO to NO_2 by ozone and only a minor decrease in nicotine concentrations when ozone is used to "clean" the air. In light of the potential for generating hazardous ozone levels indoors and the lack of scientific data supporting its efficacy, using only ozone to combat ETS in indoor air is not recommended.

Odor counteractants and **odor masking** are not truly control methods; they may apply only to specific odors and have limited effectiveness. They also add potential contaminants to the air.

EQUIPMENT

General Considerations. With a few exceptions, adsorption and chemisorption media are supplied as granules or pellets, which are held in a retaining structure that allows air being treated to pass through the media with an acceptable pressure drop at the operating airflow. Granular media have traditionally been a few millimetres in all dimensions, typically on the order of 4 × 6 or 4 × 8 U.S. mesh pellets or flakes, because these sizes have an acceptable pressure drop at the required operating conditions.

Numerous other sizes are available. Typical configurations of units in which millimetre-sized granular or pelletized media are held between perforated retaining sheets or screens are shown in Figures 4A, 4B, and 4E. The perforated retainers or screens must have holes smaller than the smallest particle of the active media. A margin without perforations must be left around the edges of the retaining sheets or screens to minimize the amount of air that can bypass the active media. Media must be tightly packed in the structure so that open passages through the beds do not develop. Aluminum; stainless, painted, plated, or coated steel; plastics; and kraftboard are all used for retainers.

Adsorptive media may also be retained in fibrous filter media or other porous support structures that can be pleated into large filters, as shown in Figures 4C and 4F. The adsorptive media must be bound to the supporting fibers in such a way that media micropores are preserved (i.e., not sealed by binders) and adequate overall adsorptive capacity is maintained. Media supported in this way are generally much smaller (down to approximately 80 mesh). Small-particle adsorbents have higher efficiency than the same adsorbent in larger particles. The smaller particles must be uniformly distributed and supported so the pressure drop of the composite is acceptable. Because the adsorbent is intimately bound to, and its performance affected by, the support structure, these adsorbers must be evaluated by tests on the complete composite structure, not the granular adsorbent alone.

Granular media adsorbers are available in two working classes: **total-** or **full-detention** and **partial-detention** units. Full-detention units initially contain the mass transfer zone totally within the bed, as depicted by the θ = 0 curve of Figure 3A. Other popular commer-

A. GRANULAR MEDIA TRAY, REFILLABLE OR DISPOSABLE

B. GRANULAR MEDIA MODULE, REFILLABLE OR DISPOSABLE

C. SIDE-ACCESS ADSORBER HOUSING WITH GRANULAR MEDIA TRAYS OR MODULES

D. VERTICAL TUBE SYSTEM

E. COMPOSITE MEDIA IN FLANGED UNITARY ADSORBER, DISPOSABLE

F. GRANULAR MEDIA SERPENTINE CELL, REFILLABLE

G. ADSORBENT-INFUSED PANEL FILTER, DISPOSABLE

H. HONEYCOMB PANEL ABSORBER, DISPOSABLE

Fig. 4   Sectional and Schematic Views of Typical Adsorber and Chemisorber Configurations

cial designs may allow the challenge gas to bypass the unit or have short residence times. Partial-detention units are called partial-bypass if large open areas are designed into the bed or device. Partial-detention units are useful when 100% control is not needed to achieve design objectives or when high recirculation rates allow them to effectively remove contaminants from a space.

Generally, in total-detention units, all the air passes through a media bed that is usually at least 0.5 in. thick, with a residence time of 0.02 s or more, although they can be much thicker and have longer residence times. At their rated flow, they have an initial efficiency of nearly 100% (full detention) for modest challenge concentrations of the contaminants they control well. Partial-detention units operated at capacity have initial efficiencies of 80% or below. They typically have lower pressure drops than full-detention units. They may allow 50% or more of the air approaching them to bypass the media bed and remain untreated, as do 50% fill honeycomb panels and some partial-bypass unit adsorbers. Similarly, some adsorbent-bonded carbon panels operating at face velocities of approximately 300 fpm or more have very low residence times and are best classed as partial-detention units even though all the air passes through the adsorber.

Equipment Configurations. Unitary adsorbers in built-up banks or **side-access housings** holding individual media-filled trays, modules, or cells, are both available. Built-up banks require space upstream of the filter bank to install the adsorbers and for maintenance. Larger equipment benefits from the maintenance simplicity of built-up front-access banks. Side-access housings are an integral part of a duct run, and are usually selected if the system is small (about 3000 cfm or less) or if in-line space is limited.

A **unitary adsorber** has either a permanent holding frame filled with multiple trays, modules, or panels, or a single, disposable box-type unit or adsorbent-bonded media cell. Unitary adsorbers incorporate channels to retain trays, modules, or panels either vertically or horizontally. Their size depends on what they are intended to hold.

Media trays (Figure 4A) vary in thickness from 0.625 to 6 in. and may be constructed of painted or stainless steel or plastic. Their height and breadth are sufficient to span the housing in which they

are placed. **Modules** (Figure 4B) are usually designed to hold media in a V-panel configuration. They may be refillable or disposable.

Panel adsorbers (Figure 4H) usually use a base of fibrous honeycomb material to hold the granular media. The efficiency and pressure drop of these panels can be controlled by the amount of media placed in each honeycomb opening; 50, 75, and 100% fills are common.

Disposable, box-type units may use multiple media-filled panels arranged in a V configuration and sealed into frames with or without headers. Fiber-adsorbent composite media may be pleated and assembled into disposable box-type unitary filters, which may be of heavy or lightweight construction depending on the filter's capacity.

Adsorbent-bonded media is often pleated into a cardboard or metal frame and provide both gaseous and particulate contamination control. These filters usually are only used for extremely light-duty peak-shaving applications because the available adsorbent is relatively limited.

A partially filled granular media holder can have a preferred orientation because the media may be able to move. For example, a vertical, 50% filled honeycomb panel adsorber has about 50% open area and 50% carbon granules in the direction of flow through the panel. The same panel adsorber, oriented horizontally in downflow, becomes a packed bed with a media thickness of about half the panel depth because the granules pack against the bottom retaining screen. In upflow, the adsorbent is lifted by the airflow and forms a packed or percolating bed against the retaining screen at the top, causing sorbent abrasion. The pressure drop and adsorption performance of each of these orientations is different. Most manufacturers rate their products in only one orientation and do not investigate other applications.

Side-access adsorber housings hold the same types of trays, modules, and panels used with unitary adsorbers. The housings have doors on one or both sides and often include channels for particulate prefilters or afterfilters. The adsorber units slide into place on rails or channels that require tight seals to prevent bypass leakage. The housings are often mounted adjacent to the air handler.

Numerous specialty and proprietary housing designs have been developed to meet stringent performance or space requirements.

Annular thick-bed designs include the U.S. M98 military protective filter (a bed of specialty carbon packaged in a cylindrical housing) and a vertical tube system, shown in Figure 4D, which is manually filled with media through a top access hatch.

Filter Housing and Adsorber Module Integrity. Performance of any air cleaner installation is limited by the integrity of the total installation. A 100% efficient filter mounted in a housing that allows 10% bypass is a 90% efficient installation. Bypass is of little consequence for low-efficiency installations because efficiency is not important and such installations generally have low pressure drop across the filter. It becomes more important for high-efficiency installations.

Generally, gas contaminant air cleaners and housings of any nominal size, if made by different manufacturers, differ slightly in dimensions and tolerances. Manufacturers are generally willing to state the overall effectiveness of a filter and housing only if they make both. Designers should consider the desired overall efficiency and ensure that the housing and filter together meet performance goals. If future efficiency upgrades are contemplated, it may be cost-effective to use a better housing than required by the initial design goals.

Filter-sealing systems must be specified to be consistent with the intended use. A partial-detention filter may appropriately be designed without any seal beyond that of the cardboard frame to filter housing. On the other hand, a thick-bed design intended for a protection application may require a knife-edge-into-gel seal developed for cleanroom applications to achieve its intended level of performance.

Many filters intended for HVAC application use foam gasketing, which may be installed on the filter or housing. If foam gasketing is used, it must be compatible with the gas stream so it does not fail over the design life. Design details that affect performance include joints (butt-joint gasket corners leak more often than dove-tail joints), cell structure (open-cell foam is more likely to be penetrated than closed), and frame or housing integrity (distortion from poor installation or shipping damage can preclude good sealing).

Further, filter seals and gasketing have finite lifetimes and require maintenance. Failure to correctly install equipment or maintain gaskets leads to increased penetration in many applications. Inspection is required at installation and periodically thereafter.

Preventing bypass is critical for protection applications (whether of people or artifacts). These applications typically use thick beds, which have the highest pressure drops and for which even low penetration is deleterious. One method of detecting significant bypass is to measure whether the filter achieves its rated pressure drop at full flow. Designers of protective air cleaning systems should consult Chapter 21 and specialty design guidance.

AIR CLEANER SYSTEM DESIGN

Air cleaner system design consists of determining and sizing the air cleaning technology to be applied, and then choosing equipment with characteristics (size and pressure drop) that can be incorporated into the mechanical design.

The gaseous contaminant control designer ideally should have the following information:

- Exact chemical identity of the contaminants present in significant concentrations
- Rates at which contaminants are generated in the space
- Rates at which contaminants are brought into the space with outdoor air
- Time-dependent performance of the proposed air cleaner for the contaminant mixture at concentration and environmental conditions to be encountered
- A clear goal concerning what level of air cleaning is needed

This information is usually difficult to obtain. The first three items can be obtained by sampling and analysis, but funding is usually not sufficient to obtain samples except in very simple contamination cases. Designers must often make do with a chemical family (e.g., aldehydes). Investigation may allow a rough estimate of contaminant generation rate based on quantity of product used daily or weekly. Experience with the particular control application or published guidance [e.g., Rock (2006) for environmental tobacco smoke] can be very helpful.

Experimental measurements of air cleaner performance are usually not available, but can be estimated using the equations in the section on Using Source Data to Predict Indoor Concentrations when the exact chemical identity of a contaminant is known. The chemical and physical properties influencing a contaminant's collection by control devices can usually be obtained from handbooks and technical publications. Contaminant properties of special importance are relative molecular mass, normal boiling point (i.e., at standard pressure), heat of vaporization, polarity, chemical reactivity, and diffusivity.

Air cleaner performance with mixtures of chemically dissimilar compounds is very difficult to predict. Some gaseous contaminants, including ozone, radon, and sulfur trioxide, have unique properties that require design judgment and experience.

Finally, design goals must be considered. For a museum or archive, the ideal design goal is total removal of the target contaminants and no subsequent desorption. For any chemical that may affect health, the design goal is to reduce the concentration to below the level of health effects. Again, desorption back into the space must be minimized. For odor control, however, 100% removal may be unnecessary and desorption back into the space at a later time with a lower concentration may be economical and acceptable.

The first step in design is selecting an appropriate adsorption medium. Next, the air cleaner's location in the HVAC system must be decided. Then the air cleaner must be sized so that sufficient media is used to achieve design efficiency and capacity goals and to estimate media replacement requirements. Finally, commercial equipment that most economically meets the needs of the application can be selected. These steps are not completely independent.

Air Cleaner Location and Other HVAC Concerns

Outside Air Intakes. Proper location of the outside air intake is especially important for applications requiring gaseous contaminant filters because outside contaminants can load the filters and reduce their operating lifetime. Outside air should not be drawn from areas where point sources of gaseous contaminants are likely: building exhaust discharge points, roads, loading docks, parking decks and spaces, etc. See Chapter 44 for more information on air inlets.

To further help reduce the amount of contaminants from outside air, at least on days of high ambient pollution levels, the quantity of outside air should be minimized.

Air Cleaner Locations. The three principal uses for gaseous contaminant control equipment in an HVAC system are

- *Outside Air Treatment.* Air-cleaning equipment can be located at the outside air intake to treat outside air only. This treatment is used principally when indoor gaseous contaminants are adequately controlled by outdoor air ventilation, but the outdoor air needs to be cleaned to achieve satisfactory air quality.
- *Bypass or Partial Supply Air Treatment.* Bypass can be achieved with a bypass duct and control damper or by installing an air cleaner that allows substantial bypass. Partial supply air treatment may be appropriate where a specific threshold contamination level is targeted, when outside and inside contamination rates are known, and the required level of reduction is small to moderate.
- *Full Supply Air Treatment.* Full treatment achieves the best contaminant control, but with the highest cost and largest equipment volume. This approach is most often used in ventilation

strategies that reduce outdoor air while maintaining good indoor air quality.

When outdoor air quality is adequate, treatment of recirculated ventilation air alone may be adequate to control indoor contaminants such as bioeffluents. Full or bypass treatment of the supply air may be appropriate, depending on the source strength.

Media Selection

Media selection is clear for many general applications, but for others is a matter of judgment. In general, gaseous contaminants that have the same or higher boiling point as water can be removed by physical adsorption using standard activated carbon. Those with a lower boiling point usually require chemisorption for removal. Figure 5 shows the media and equipment selection process.

In practice, different examples of the same application may be served well by somewhat different media selections. Any guidance must be tempered by consideration of the specifics of a particular location, and guidance given by different manufacturers may differ somewhat. Table 6 consolidates general guidance for numerous commercial applications from multiple manufacturers. Within each media group, the applications are listed alphabetically; similar applications appear in more than one list, because some applications may be well served with either a single medium or by a blend, with the best choice determined by the specific contaminants present (both chemical identity and concentration.) Acceptability may hinge on a specific, hard-to-control chemical that is present at one site but not at another. Adsorption capacity for a particular chemical or application may vary from these guidelines with changes in

- **Competitive adsorption.** Multiple contaminants confound performance estimates.
- **Temperature.** Activity decreases with a temperature increase.
- **Humidity.** Effect of humidity (generally for rh > 50%) depends on the contaminant. Carbon capacity for water-miscible solvents increases; capacity for immiscible or partially miscible solvents decreases.
- **Concentration.** Increased contaminant concentration improves activity.

Table 7 provides a general guide to selection of media to control particular chemicals or types of chemicals. As was true of Table 6,
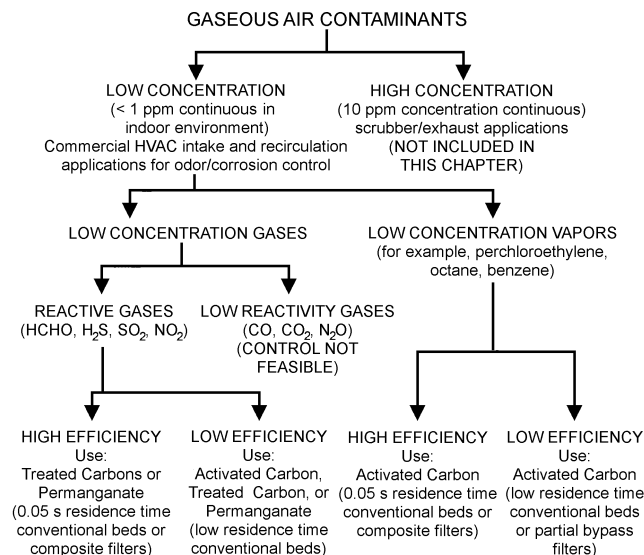
some difference in opinion exists as to which media is best, as indicated for the chemicals followed by an exclamation point.

Sizing Gaseous Contaminant Control Equipment

There are currently two common sizing approaches: using manufacturers' guidance, and using the absorbent performance equations in the section on Using Source Data to Predict Indoor Concentrations. Adsorbent performance and contaminant concentration data required to use the equations are not generally available; however, test methods are being developed that may allow broader use of performance equations.

Manufacturers' Design Guidance. Most manufacturers of control system components offer selection guidance. Some of the methods for traditional granular beds are summarized here. Note that inclusion of this information or exclusion of other methods does not imply acceptance or endorsement by ASHRAE, but is meant to be an abbreviated overview of present-day practice. The general expectation is of an HVAC application service life of 9 to 18 months for a 3120 h air-conditioning year. These values are simply a summary of conventional wisdom directed at meeting that goal, and they can be substantially in error. The manufacturer's recommendations have been annotated to put the entire discussion in the same terminology.

One manufacturer divides HVAC and IAQ applications into three categories and recommends equipment selection based on efficiency and activated carbon weight, as follows:

1. Heavy-duty outdoor air or mixed air IAQ applications with a relatively constant VOC generation rate and relatively constant moderate to severe outdoor air pollution:

   - For cleaned-air-equivalent air quality (i.e., air cleaned well enough to substitute for outdoor air), use equipment with >90% efficiency and 75 to 100 lb of high-grade carbon per 2000 cfm For a 1 in. bed in common commercial unitary adsorbers, this corresponds to a 0.1 s residence time.
   - With severe outdoor air pollution from nearby sources, it may be necessary to size equipment at 90 lb of carbon per 1000 to 1400 cfm, which corresponds to 0.14 to 0.2 s residence time.

2. For medium-duty return or mixed air IAQ applications with constant low to moderate VOC generation and cleaned-air-equivalent air quality, use equipment efficiencies of 20 to 90% and 8 to 75 lb of carbon per 2000 cfm. This corresponds to partial bypass equipment at the low-efficiency end and ranges up to about 0.08 s residence time at the high-efficiency end.

3. For light-duty mixed air IAQ applications with intermittent low to high VOC generation and an intermittent low to high outdoor air pollution load, use equipment efficiencies of >75% for odor control, which corresponds to a partial bypass design.

Another manufacturer offers a variety of adsorbers with both plain and chemically impregnated activated carbon. After determining the application's residence time range,

1. Choose the hardware configuration: replacement cells or disposable units.
2. Specify face size and depth, and verify that the air quantity is within stated limits for residence time.
3. Select the proper chemistry (impregnation) for the application and the adsorber's location in the airstream.

A third manufacturer holds that, in most IAQ investigative work and applications, neither the total load nor specific contaminant is known. A broad-based control design approach is then usually recommended, consisting of two adsorber banks: activated carbon, followed by potassium permanganate-impregnated alumina. Sometimes these two media are combined into one bank because of space or pressure drop limitations.

Fig. 5 Media and Equipment Selection Schematic
(Adapted with permission. ©1992 Extraction Systems, Inc.)

Table 6   Media Selection by Commercial Application

Commercial Application	Contaminants/Species
Activated Carbon or Carbon/Permanganate-Impregnated Alumina Blend	
Airport terminals (air side and non-air side), art studios, athletic clubs, auditoriums, banks (customer area), banquet rooms, beauty salons, bus terminals, clinics, darkrooms, decal application, dentists'/doctors' offices, dry cleaners (dust area), factories (office area), florists, grocery stores, kitchen exhausts, locker rooms, office buildings, painted rooms, pharmacies, photo stores, photographic studios, physiotherapy, recreation halls, rendering plants, stores	Multiple volatile organic gases/solvent vapors and inorganic gases; possibly some gases poorly adsorbed by carbon Multiple organics and inorganics, fumes, food odors, body odors, floral scents, odorous fumes, moldy odors, paint fumes, furniture, ETS, NO_x, SO_x, O_3, mercaptans, valeric acid, formaldehyde
Activated Carbon/Permanganate-Impregnated Alumina Blend	
Bars, bingo halls, brasseries, cafeterias, casinos, cocktail lounges, conference rooms, correctional facilities, funeral homes, geriatrics, hospitals, hotels (smoking, renovation), ICUs, libraries, lounges, lunch rooms, motels, museums, night clubs, nurseries, paint shops (office), penal institutions, projection booths, psychiatric institutions and wards, public toilets, restaurants, segregated smoking rooms, storage rooms, theaters, waiting rooms	Mixed gases/ETS; good possibility of volatile organic gases and/or solvent vapors ETS, body odors, urine, excreta, perfume, multiple odors, food odors, kitchen fumes, food, furniture/furnishings offgassing, multiple organics and inorganics, paint
Activated Carbon or Permanganate-Impregnated Alumina	
Barber shops, dining rooms	Mixed gases, ETS, food odors
Carbon/Permanganate Blend or Permanganate-Impregnated Alumina	
Embalming rooms, fruit/vegetable storage, greenhouses	Multiple organics; organic gases poorly sorbed by activated carbon Multiple organics, formaldehyde, ethylene
Activated Carbon or Permanganate-Impregnated Alumina/Acid-Impregnated Carbon Blend	
Garbage disposal areas	Mixture of volatile organics and inorganics with ammonia
Permanganate-Impregnated Alumina	
Autopsy rooms, banks (vault area), fish markets, hospitals (autopsy), morgues	Volatile organic gases poorly adsorbed by activated carbon Formaldehyde, trimethyl amine
Permanganate-Impregnated Alumina/Acid-Impregnated Carbon Blend	
Pet shops, animal holding rooms, veterinary hospitals	Mixed organic gases with significant ammonia urine, excreta, animal odors
Activated Carbon/Acid-Impregnated Carbon Blend	
Printing plants	Mixed hydrocarbons and ammonia
Acid-Impregnated Carbon	
Fertilizer plants (office)	Largely ammonia

Notes: Permanganate impregnant is potassium permanganate. Acid impregnants vary.   ETS = environmental tobacco smoke

- For light-duty applications, this manufacturer recommends particulate filter media infused with either carbon or permanganate media and pleated into a traditional filter design.
- For medium-duty applications, granular media are used in 1 to 3 in. deep refillable or disposable bulk-fill modules for increased efficiency and service life.
- When specific contaminants and concentrations are known, granular media are specially impregnated and bulk-fill modules or deep beds (up to 48 in.) are used. The latter are recommended for critical applications such as corrosion prevention in computerized control rooms.

A fourth manufacturer evaluates and specifies all of its molecular filters by measuring the initial removal efficiency of the whole filter installed in its frame, and measures the amount of contaminant removed as adsorbent capacity is consumed during the test. Curves of efficiency versus capacity are used to guide the customer through the selection process.

Another form of manufacturer's guidance is given in Table 8, which gives suggested packed-bed residence time ranges, developed for the 4 × 6 or 4 × 8 mesh coconut shell carbon typically used in packed beds, for various applications. Residence times in Table 8 are appropriate for moderate to thick beds of large-particle carbons, but do not apply universally to commercial adsorbers. Different ways of arranging the carbon, different adsorbents, or different carbon granule sizes change the residence time required to get a particular result. This is especially true of very finely dispersed activated carbon, which has very fast adsorption kinetics. In addition, the geometry and packaging of some adsorbent technologies make computation of residence time difficult. For instance, cylindrical beds with radial flow have air velocities that decrease from the center to the periphery, so special computational techniques are needed to put residence time on the same basis as for a flat bed. Similarly, the flow pattern in pleated fiber/carbon composite media is difficult to specify, making residence time computation uncertain. Therefore, although residence times can be computed for partial-bypass filters, fiber-adsorbent composite filters, or fiber-bonded filters, they cannot be compared directly with those in Table 8, and serve more as a rating than as an actual residence time. By applying residence time as a rating, manufacturers may publish equivalent residence time values that say, in effect, that this adsorber performs the same as a traditional deep bed adsorber. No standard test exists to verify such a rating.

Tables 6 and 7 provide guidance in selecting sorbent media. Both manufacturers' guidance and absorbent performance Equations (2) to (7) are used to size equipment. A manufacturer's guidance is often followed because adsorbent performance and contaminant concentration data required to use the equations are not generally available.

When calculating adsorber size, use the following approach:

1. Choose an adsorbent suited to the contaminant.
2. Pick an appropriate efficiency for the adsorber (complete removal or partial bypass), depending on the contaminant.
3. Choose a desired operating adsorber end point of 10%, 50%, or other breakthrough, depending on the application and allowable steady-state concentration. A building ventilation performance model, with the adsorber appropriately positioned, allows

Table 7   Media Selection by Contaminant

Gaseous Contaminant	PPIA	AC	AIC	BIC	Gaseous Contaminant	PPIA	AC	AIC	BIC	Gaseous Contaminant	PPIA	AC	AIC	BIC
Acetaldehyde	*	0			Dichlorofloromethane		*			Methyl formate	0	*		
Acetic acid (!)	*	0		0,*	R-114 (see note)		*			Methyl isobutyl ketone	0	*		
Acetic anhydride (!)	*,0	*		0	Diethylamine	0	*			Methyl sulfide	*			
Acetone (!)	*	0			Dimethylamine		*	0		Methyl vinyl ketone	0	*		
Acetylene	*				Dioctyl phthalate		*			Naphtha		*		
Acrolein	*	0			Dioxane	*	0			Naphthalene		*		
Acrylic acid (!)	*	*		0	Ethanol	*	0			Nicotine	*	0		
Allyl sulfide	*	0			Ethyl acetate	0	*			Nitric acid				*
Ammonia (NH₃)			*		Ethyl chloride (!)	*,0	0,*			Nitric oxide (NO)	*			0
Aniline	0	*			Ethylene (C₂H₄)	*				Nitrobenzene		*		
Arsine	*				Ethylene oxide	*	0			Nitrogen dioxide	*			0
Benzene		*			Ethyl ether	0	*			Nitromethane	*			
Borane (!)	*	0,0			Ethyl mercaptan (!)	*,*	0		0	Nitrous oxide				*
Bromine		*			Formaldehyde	*				Octane (!)	0	*,*		
1,3 Butadiene	*	0			Gasoline	*				Ozone (O₃) (!)	0	*,*		
Butane		*			General halocarbons		*			Perchloroethylene	0	*		
2-Butanone	*	0			General hydrocarbons	0	*			Peroxy acetyl nitrate (PAN)		*		
2-Butoxyethanol	0	*			General VOC	0	*			Phenol	0	*		
Butyl acetate (!)	*,0	0,*			Heptane		*			Phosgene	0	*		
Butyl alcohol	0	*			Hydrogen bromide		0		*	Phosphine	*			
Butyl mercaptan	0	*			Hydrogen chloride		0		*	Putrescine	*	0		
Butylene	0	*			Hydrogen cyanide	*				Pyridine (!)	*	*		
Butyne	0	*			Hydrogen fluoride	*			*	Skatole	0	*		
Butyraldehyde	0	*			Hydrogen iodide	0				Silane	*			
Butyric acid		*		0	Hydrogen selenide					Stoddard solvent	*			
Cadaverine	0	*			Hydrogen sulfide	*			*	Stibine	*			
Camphor		*			Iodine		*			Styrene (!)	0	*,*		
Carbon dioxide (CO₂)	Carbon w/catalyst				Iodoform	0	*			Sulfur dioxide	*			*
Carbon disulfide	0	*			Isopropanol	0	*			Sulfur trioxide	*			*
Carbon monoxide (CO)	Carbon w/catalyst				Kerosene		*			Sulfuric acid		0		*
Carbon tetrachloride		*			Lactic acid		*			Toluene		*		
Chlorine (Cl₂)				*	Menthol	0	*			Triethylamine		0	*	
Chloroform		*			Mercury vapor	Impreg. AC				Trichlorethylene		*		
Creosote (!)	*,0	0,*			Methanol	0	*			1,1,1, trichloroethane (!)	*	0,*		
Cyclohexane		*			Methyl acrylate	0	*			R-11 (see below)		*		
Cyclohexanol	0	*			Methyl bromide (!)	0,*	*			Turpentine	0	*		
Cyclohexanone	0	*			Methyl butyl ketone (!)	*,0	0,*			Urea (!)	0	*,*		
Cyclohexene		*			Methyl cellosolve acetate	0	*			Uric acid (!)	*	*		0,0
Decane		*			Methylchloroform		*			Vinyl chloride		*		
Diborane	*				Methylcyclohexane		*			Xylene		*		
Dichlorobenzene		*			Methylene chloride		*							

* = primary media selection for contaminant; 0 = secondary media selection.
PPIA = potassium-permanganate-impregnated alumina; AC = activated carbon;
 AIC = acid-impregnated carbon; BIC = base-impregnated carbon
R-114 is dichlorotetrafluoroethane; R-11 is trichlorofluoromethane.

Comments: Some contaminant molecules have isomers that, because they have different physical properties (boiling point, vapor pressures), require different treatment methods. For some contaminants, preferred treatment is ion exchange or another (nonlisted) impregnated carbon. For some contaminants, manufacturer recommendations differ. "!" is used in these cases.

calculation of the expected indoor concentration at various breakthroughs and efficiencies.

4. Obtain a measurement or estimate of breakthrough time at adsorber use conditions as developed in step (3).

5. Determine the changeout rate for the adsorbent as set by the breakthrough time.

6. Match the computed design requirements to available air cleaning equipment and specify.

Special Cases

Ozone reaches an equilibrium concentration in a ventilated space without a filtration device. It does so partly because ozone molecules react to form oxygen, but also because it reacts with people, plants, and materials in the space. This oxidation is harmful to all three, and therefore natural ozone decay is not a satisfactory way to control ozone except at low concentrations (<0.1 ppmv).

Fortunately, activated carbon adsorbs ozone readily, both reacting with it and catalyzing its conversion to oxygen.

Radon is a radioactive gas that decays by alpha-particle emission, eventually yielding individual atoms of polonium, bismuth, and lead. These atoms form ions, called radon daughters or radon progeny, which are also radioactive; they are especially toxic, lodging deep in the lung, where they emit cancer-producing alpha and beta particles. Radon progeny, both attached to larger aerosol particles and unattached, can be captured by particulate air filters. Radon gas itself may be removed with activated carbon, but in HVAC systems this method costs too much for the benefit derived. Control of radon emission at the source and ventilation are the preferred methods of radon control.

Museums, libraries, archives, and similar applications are special cases of air cleaner design for protection, and may require very efficient air cleaning; see Chapter 21 for specifics.

Table 8 Suggested 4 × 6 or 4 × 8 Mesh Coconut Shell Carbon Residence Time Ranges

Application	Residence Time,[a] s
HVAC odor control applications for indoor air quality	
Light to medium duty	0.03 to 0.07
Heavy duty	0.06 to 0.14
Cleanroom corrosion control	
Recirculation	0.03 to 0.07
Intakes	0.03 to 0.14
Industrial corrosion control	0.12 to 0.28+
(refineries, wastewater, pulp, etc.)	
Corrosive/reactive low-level exhaust applications	0.12 to 0.28+
Toxic gas control[b]	0.28+
Museums	
Standard applications	0.06 to 0.12
Recirculation applications	0.03 to 0.07
Critical air intake	0.28+
Critical recirculation application	0.12 to 0.28
Nuclear applications	0.12 to 0.28+

Notes: [a]All residence times given are rules of thumb using 4 × 6 or 4 × 8 mesh carbon in granular beds for the application indicated. Other carbon packages, such as pleated filters containing finely divided carbon, may be dramatically different. Particularly at low (ppb) contaminant concentrations, well-designed pleated carbon filters can be very efficient and have adequate capacity.
[b]Design for toxic gas control must include appropriate overdesign and fail-safe provisions for all equipment used.
Source: Adapted and used with permission. ©1992 Extraction Systems, Inc.

Table 9 Items Included in Economic Comparisons Between Competing Gaseous Contaminant Control Systems

Capital Costs	Operating Costs
Added filtration equipment	Replacement or reactivation of gaseous contaminant filter media
Fan	
Motor	Disposal of spent gaseous contaminant filter media
Controls	
Plenum	Added electric power
Spare media holding units	Maintenance labor
Floor space	

Gas-phase air cleaners for **building protection** applications, whether to protect occupants against industrial accidents or deliberate acts, cannot reasonably stand alone. It makes little sense to design a complex system that can be easily overcome by physical acts. Air cleaner design alone is not enough. Air cleaning must be part of a complete and in-depth security program. The designer must have a scenario or series of scenarios against which to design protective systems.

Because a given air-cleaning technology may not protect against all challenges, protection against deliberate acts requires a robust design. The air-cleaning technology can be chosen to protect against the most challenging contaminant. Once the challenge contaminants are identified, a more rigorous application of the design method described previously is applied. Military specification hardware is generally suitable, although high-end commercial designs can provide significant protection. Testing of the installed filters is generally required, maintenance costs are significant, and the cost in space allocated to the installation, energy, and capital is high.

U.S. government guidance for the designer is available online (FEMA 2003a, 2003b; NIOSH 2002, 2003). The FEMA Web site also includes a number of other applicable documents. For additional guidance, see Chapter 58.

Energy Concerns

Pressure drop across the contaminant filter directly affects energy use. Data on the resistance of the filter as a function of airflow and on the resistance of the heating/cooling coils must be provided by the manufacturer. Currently, no standard test of pressure drop across a full-scale gaseous air cleaner is specified, but users can require that the initial pressure drop measurement from the particulate test (ASHRAE *Standard* 52.2) be conducted and reported. In addition to the gaseous contaminant filter itself, pressure drop through the housing, any added duct elements, and any particulate filters required up- and/or downstream of the gaseous contaminant filter must be included in the energy analysis.

Choosing between using outside air only and outside air plus filtered recirculated air is complex, but can be based on technical or maintenance factors, convenience, economics, or a combination of these. An energy-consumption calculation is useful. Replacing outdoor air with filtered indoor air reduces the amount of air that must be conditioned at an added expense in recirculation pressure drop. Outdoor air or filtered recirculated air may be used in any ratio, provided the air quality level is maintained. Janssen (1989) discusses the logic of these requirements.

Where building habitability can be maintained with ventilation alone, an economizer cycle is feasible under appropriate outdoor conditions. However, economizer mode may not be feasible at high humidities, because high humidity degrades the performance of carbon adsorbers.

Economic Considerations

Capital and operating costs for each competing system should be identified. Chapter 36 provides general information on performing an economic analysis. Table 9 is a checklist of filtration items to be considered in an analysis. It is important that the fan maintain adequate flow with an in-line air cleaner in place. If a larger blower is required, space must be available. Modifying unitary equipment that was not designed to handle the additional pressure drop through air-cleaning equipment can be expensive. With built-up designs, the added initial cost of providing air cleaners and their pressure drop can be much less because the increases may be only a small fraction of the total.

The life of the adsorbent media is very important. The economic benefits of regenerating spent carbon should be evaluated in light of the cost and generally reduced activity levels of regenerated material. Regeneration of impregnated carbon or any carbon containing hazardous contaminants is never permitted. Spent alumina- or zeolite-based adsorbents also cannot be regenerated.

SAFETY

Gaseous contaminant removal equipment generally has a low hazard potential. Contaminant concentrations are low, temperature is moderate, and the equipment is normally not closed in. Alumina- or zeolite-based media do not support combustion, but carbon filter banks have been known to catch fire, usually from an external source such as a welder's torch. Check local codes and fire authorities for their regulations on carbon. One authority requires automatic sprinklers in the duct upstream and downstream of carbon filter banks. As a minimum, a smoke detector should be installed downstream of the filter bank to shut down the fan and sound an alarm in case of fire.

Access for safe maintenance and change-out of adsorbent beds must be provided. Adsorbers are much heavier than particulate filters. Suitable lifting equipment must be available during installation and removal to prevent injury.

If adsorbent trays are to be refilled on site, safety equipment must be provided to deal with the dust this generates. Hooding, dust masks, and gloves are all required to refill adsorber trays from bulk containers.

INSTALLATION, START-UP, AND COMMISSIONING

This section provides general guidance installing gaseous contaminant removal equipment. Most manufacturers can also provide complete details and drawings for design.

Particulate Filters. A minimum 25 to 30% efficiency particulate filter (per ASHRAE *Standard* 52.1) should be installed ahead of the adsorber bank. Higher efficiency is desirable. Adsorbers and chemisorbers cannot function properly if their surfaces are covered and their pores clogged with dirt. If the air is extremely dirty (e.g., from diesel exhaust), the filter should have a much higher efficiency. One manufacturer requires a 90 to 95% efficiency filter for such applications. Weschler et al. (1994) report that carbon service life for ozone control was lengthened by using improved prefiltration.

Afterfilters are often used in critical applications where dust from media at start-up is likely, or where vibration of the adsorber bank may cause granular media to shed particles. These filters are frequently 25 to 30% efficiency, but higher efficiencies may be needed in some applications.

Equipment Weight. Adsorption equipment is much heavier than particulate filtration equipment, so supporting structures and frames must be designed accordingly. A typical 24 by 24 in. adsorber consisting of a permanent holding frame and sorbent-loaded trays has an installed weight of approximately 200 lb.

Minimize or Eliminate Bypass. Adsorbers and ducts in the outside air supply and in exhaust from hoods must be tightly sealed to prevent bypass of contaminants. Bypass leakage is not critical in most recirculating indoor air systems, but it is good practice to caulk all seams between individual holding frames. Granular media settles and compacts, and media retainers, such as trays or modules, must be loaded with media following manufacturers' recommendations to eliminate bypass through the media bed.

When to Install Media. When to install adsorbers in their holding frames depends on building circumstances. If they are installed at the same time as their holding frames and if the HVAC is turned on during the latter phases of construction, the adsorbers will adsorb paint and solvent vapors and other contaminants before the building is ready for beneficial occupancy. In some situations, adsorbing vapors and gases in the ventilation system before official start-up may be desired or needed. However, adsorber life will be reduced correspondingly. If adsorber frames are not loaded until the building is ready for occupancy, the unadsorbed contaminants may seriously reduce the initial indoor air quality of the building. Thus, shortened life is an acceptable trade-off for the quality of air at the time of occupancy (NAFA 1997). If the media are not in place during fan testing, the test and balance contractor must be instructed to place blank-offs or restrictions in the frames to simulate adsorber pressure drop. The HVAC designer's job specifications must clearly state when media are to be installed.

Pressure Gages. If prefiltration is adequate, adsorber pressure drop will not increase during normal operation. A pressure-drop-measuring device (gage or manometer) is thus not required as it is for a particulate filter bank. However, a gage may be useful to detect fouling or unintentional bypass. If the prefilters or afterfilters are installed immediately adjacent to the adsorbers, it may be more feasible to install the gage across the entire assembly.

Provision for Testing. At any time after installation of new media, determining the remaining adsorbent capacity or operating life may be required. (See the section on When to Change Media under Operation and Maintenance.) The installation should provide access ports to the fully mixed air stream both up- and downstream of the air cleaner. If media samples will be removed to determine remaining life, access must be provided to obtain those samples. No standard method for field evaluation of media life currently exists.

Start-Up and Commissioning

Special procedures are not required during start-up of an air handler with adsorbers. The testing and balancing contractor normally is required to measure and record resistance of all installed filter banks, including adsorbers, for comparison with design conditions.

The commissioning authority may require an activity test on a random sample of media to determine if the new media suffered prior exposure that reduced its life or if it meets specifications. An in situ air sampling test may also be required on the adsorber filter bank; however, no standard method for this test exists. See Chapter 42 for more on commissioning.

OPERATION AND MAINTENANCE

Bypass units and filters with adsorbent-infused media require frequent changing to maintain even low efficiency, but frequent maintenance is not required for complete removal units. Complete removal media adsorbers usually have a replaceable cell that cannot be regenerated or reactivated. This section covers maintenance of complete removal equipment with refillable trays or modules only.

When to Change Media

The changeout point of an adsorbent is difficult to determine. Sometimes media are changed when breakthrough occurs and occupants complain; but if the application is sensitive, tests for estimated residual activity may be made periodically. A sample of the media in use is pulled from the adsorber bank or from a pilot cell placed in front of the bank. The sample is sent to the manufacturer or an independent test laboratory for analysis, and the changeout time is estimated knowing the time in service and the life remaining in the sample.

In corrosion control installations, specially prepared metal "coupons" are placed in the space being protected by the adsorbent. After some time, usually a month, the coupons are sent to an analytical lab for measurement of corrosion thickness, which indicates the effectiveness of the gaseous contaminant control and provides an indication of system life. A standardized methodology for these tests is described in ISA *Standard* 71.04.

Replacement and Reactivation

Replacing media in permanent adsorber trays or modules is not the same as reactivation (regeneration), which is restoring spent activated carbon media to its original efficiency (or close to it). In some unit operations in some industrial applications (e.g., pressure swing adsorption), spent carbon is regenerated in special high-temperature vessels in the absence of oxygen to drive off contaminants. Chemisorber modules can be replaced (media changed), but chemisorber media, including impregnated carbon, cannot be regenerated.

Building operating personnel may choose to dump and refill trays and modules at the site after replacing those removed with a spare set already loaded with fresh media. They may also choose to dump the trays locally and send the empty trays to a filter service company for refilling, or they may simply exchange their spent trays for fresh ones. Disposing of spent sorbent by dumping must be limited to building air quality applications where no identifiable hazardous chemicals have been collected.

ENVIRONMENTAL INFLUENCES ON AIR CLEANERS

Environmental conditions, particularly temperature and humidity, affect the performance of most gaseous contaminant control equipment. Physical sorbents such as activated carbon are particularly susceptible. The user should confirm performance for any control device at the expected normal environmental conditions as well as at extremes that might be encountered during equipment outages. The following information is an overview.

High relative humidity in the treated airstream lowers efficiency of physical adsorbers, such as carbon, because of competition for sorption sites from the much more numerous water molecules. Often, performance is relatively stable up to 40 to 50% rh, but some compounds can degrade at higher humidities. The chemical nature of the contaminant(s) and the concentration both affect performance degradation as a function of relative humidity. On the other hand, very low relative humidities may make some chemisorption impossible. Therefore, media performance must be evaluated over the expected range of operation, and the relative humidity and temperature of the gaseous contaminant control should be held within design limits.

The effect of relative humidity swings can be better understood by considering a hypothetical adsorber with a saturation capacity for a contaminant and inlet concentration of 10% at 50% rh and 5% at 70% rh. Over an extended period at its normal operating condition of 50% rh, the sorbent might reach a loading of 2%. At this point a humidity swing to 70% rh would not cause a problem, and the sorbent could load up to 5% capacity. Should the humidity then swing back to 50%, the sorbent could continue to adsorb up to 10% by weight of the contaminant. However, if the sorbent were loaded to 8% by weight at 50% rh and the humidity rose to 70% rh, the carbon would be above its equilibrium capacity and desorption would occur until equilibrium was reached.

Similarly, swings in temperature and contaminant concentration can affect physical sorbent performance. Increasing temperature reduces capacity, and increasing concentration increases capacity. Additionally, changes in the identity of the contaminant in the airstream can affect overall performance as strongly sorbed contaminants displace weakly held contaminants.

All adsorption media have a modest ability to capture dust particles and lint, which eventually plug the openings in and between media granules and cause a rapid rise in the pressure drop across the media or a decrease in airflow. All granular gaseous adsorption beds need to be protected against particle buildup by installing particulate filters upstream. A prefilter with a minimum ASHRAE *Standard* 52.1 dust-spot efficiency of 25 to 30% is recommended.

Vibration breaks up the granules to some degree, depending on the granule hardness. ASTM *Standard* D3802 describes a test for measuring the resistance of activated carbon to abrasion. Critical systems using activated carbon require hardness above 92%, as described by *Standard* D3802.

Adsorption and chemisorption media sometimes accelerate corrosion of metals they touch. Consequently, media holding cells, trays, and modules should not be constructed of uncoated aluminum or steel. Painted steel or ABS plastic are common and exhibit good material service lives in many applications. Coated or stainless steel components may be required in more aggressive environments.

TESTING MEDIA, EQUIPMENT, AND SYSTEMS

Testing may be conducted in the laboratory with small-scale media beds or small pieces of treated fabric or composite material; on full-scale air cleaners in a laboratory test rig capable of generating the test atmosphere; or in the field. Laboratory tests with specific challenge gases are generally intended to evaluate media for developmental, acceptance, or comparative purposes. Full-scale tests using specific challenge contaminants are required to evaluate a complete adsorber as constructed and sold, and ultimately are needed to validate performance claims. Field tests under actual job conditions are used to ensure that the air cleaners were properly installed and to evaluate remaining media life.

Laboratory Tests of Media and Complete Air Cleaners

Small granular media samples have been tested in a laboratory for many years, and most manufacturers have developed their own methods. ASTM *Standard* D5228 describes a test method, but it is not entirely applicable to HVAC work because indoor air tends to have a wide range of contaminants at concentrations several orders of magnitude lower than used in testing.

Fundamental Media Properties Evaluation. The test used to evaluate fundamental properties of sorption media is static: measurement of the adsorption isotherm. In this test, a small sample of the adsorbent media is exposed to the pollutant vapor at successively increasing pressures, and the mass of pollutant adsorbed at each pressure is measured. The low-pressure section of an isotherm can be used to predict kinetic behavior, although the calculation is not simple. For many years, the test outlined in ASTM *Standard* D3467, which measured a single point on the isotherm of an activated carbon using carbon tetrachloride (CCl_4) vapor, was widely used for specifying performance of activated carbons. The test has been replaced by one described in ASTM *Standard* D5228, which uses butane as a test contaminant, because of carbon tetrachloride's toxicity. A correlation has been developed between the results of the two procedures so that users accustomed to CCl_4 numbers can recognize the performance levels given by ASTM D5228. It is a qualitative measure of performance at other conditions, and a useful quality control procedure. Another qualitative measure of performance is the Brunauer-Emmett-Teller (BET) method (ASTM *Standard* D4567), in which the surface area is determined by measuring the mass of an adsorbed monolayer of nitrogen. The results of this test are reported in square metres per gram of sorbent or catalyst. This number is often used as an index of media quality, with high numbers indicating high quality.

Small-Scale Dynamic Media Testing. ASHRAE is developing *Standard* 145.1, a flow-through test of media at small scale (about 2 in. diameter) and relatively high concentration (100 ppm). The test is intended to provide data for meaningful comparisons of media. *Standard* 145.1 is being developed based on several publications describing similar test procedures. Steady concentrations of a single contaminant are fed to a media bed, and the downstream concentration is determined as a function of the total contaminant captured by the filter (ASTM 1989; Mahajan 1987, 1989; Nelson and Correia 1976).

Because adsorber performance is a function of concentration, testing at high concentrations does not directly predict performance at low concentrations. The corrections described in the section on Physical Adsorption must be applied. If attempts are made to speed the test by high-concentration loading, pollutant desorption from the filter may confuse the results (Ostojic 1985). An adsorber cannot be tested for every pollutant, and there is no general agreement on which contaminants should be considered typical. Nevertheless, tests run according to the previously mentioned references do give useful measures of filter performance on single contaminants, and they do give a basis for estimates of filter penetrations and filter lives. Filter penetration data thus obtained can be used as P in Equations (3), (4), and (7) to estimate steady-state indoor concentrations.

VanOsdell et al. (2006) presented data from ASHRAE Research Project RP-792 showing that, for particular VOCs, tests at high concentration may be extrapolated to indoor levels. In addition, tests of a carbon with one chemical, toluene, are used to predict breakthough times for four other chemicals with modest success. The breakthrough times correlated well on a log-log plot of breakthrough time versus challenge concentration, and the predictions, based only on chemical properties and toluene and carbon performance data, were within approximately 100% of measured.

Because physical adsorbers, chemisorbers, and catalysts are affected by the temperature and relative humidity of the carrier gas and the moisture content of the filter bed, they should be tested over the range of conditions expected in the application. Contaminant capture and reaction product generation need to be evaluated by sweeping the test filter with unpolluted air and measuring downstream concentrations. Reaction products may be as toxic, odorous, or corrosive as captured pollutants.

Flow-Through Laboratory Tests of Complete Air Cleaners.
Flow-through tests of complete air cleaners are the full-scale system test analog of the media tests described previously. In critical applications, such as chemical warfare protective devices and nuclear safety applications, sorption media are evaluated in a small canister, using the same carrier gas velocity as in the full-scale unit. The full-scale unit is then checked for leakage through gaskets, structural member joints, and thin spots or gross open passages in the sorption media by feeding a readily adsorbed contaminant to the filter and probing for its presence downstream (ASME *Standard* AG-1). Some HVAC filter manufacturers perform full-scale laboratory testing routinely for development and testing.

Chamber Decay Laboratory Tests of Complete Air Cleaners.
Gaseous contaminant control devices can be tested in sealed chambers by recirculating contaminated air through them and measuring the decay of an initial contaminant concentration over time. Chamber decay tests are generally used for devices that physically cannot be tested in a duct, or that have single-pass efficiencies so low that they cannot be reliably measured using up- and downstream measurements. The procedures used are gaseous contaminant analogs to the Association of Home Appliance Manufacturers (AHAM) particulate air cleaner test method, but no consensus test standard exists and test methods vary between laboratories. Decay tests can provide valuable data, but the results are affected by factors extraneous to the air cleaner itself, such as errors introduced by adsorption on the chamber surfaces, leaks in the chamber, and the drawing of test samples. Robust test quality assurance and quality control are required to obtain meaningful data. Daisey and Hodgson (1989) compared the pollutant decay rate with and without the control device to overcome these uncertainties.

Field Tests of Installed Air Cleaners

Gaseous contaminant air cleaners are expensive enough to place a premium on using their full capacity. For odor control applications, the most reliable measure of the continued usefulness of gaseous contaminant air cleaners may be a lack of complaints, and complaints often serve as early indicators of exhausted beds. This approach is not acceptable for toxic contaminants, for which more formal procedures must be used. Unfortunately, and despite significant effort, there is not a simple, accepted standard for field-testing gaseous air-cleaning equipment. Two approaches have been used: (1) laboratory testing of samples of media removed from the field and (2) in situ upstream/downstream gas measurements using the ambient contaminant(s) as the challenge.

The classic and still widely used technique of evaluating the status of a granular air cleaner in the field is to remove a small sample and ship it to a laboratory. Media manufacturers offer this service. The sample needs to be representative of the air cleaner, so should be obtained from near the center of the air cleaner. Consolidated multiple small samples are more representative of the air cleaner than one larger sample. The sample needs to be handled and shipped so that it remains representative when it reaches the laboratory; laboratories can suggest procedures. Given a representative sample and good handling, sampled media test results give a good indication of the state of a media bed.

Unfortunately, media sampling as a field-testing procedure has disadvantages. First, it applies only to granular media that can be sampled; cutting a hole in a bonded or pleated media product to obtain a sample destroys the filter. In addition, opening a granular media air cleaner to obtain samples is sufficiently disagreeable to prevent its frequent application.

These disadvantages have led to attempts to find more convenient ways to evaluate filters in the field. The most widely used alternative approach is to sample the air up- and downstream of the filter and use the ratio to estimate the remaining filter capacity.

Field tests of gaseous contaminant air cleaners are conducted using the same general techniques discussed under contaminant measurement and analysis. Depending on the contaminant, type of air cleaner, and application, field testing can be accomplished with active or passive sampling techniques. Liu (1998) discussed the relative merits of the various techniques. Either may be superior in any given case. For indoor air applications with relatively constant contaminant sources, passive samplers have advantages by capturing an integrated sample and being more economical. (Real-time samplers are used infrequently in this role.)

Up- and downstream measurements are evaluated by converting them to efficiency or fractional penetration and comparing them to measurements made at the time of installation. Because gaseous challenge contaminants cannot be injected into the HVAC system in occupied buildings, the up- and downstream samplers are exposed only to the ambient contaminants, which usually vary in nature and concentration. This complicates interpretation of the data, because air cleaner efficiency varies with concentration and nature of the contaminant. Efficiency from field samples is most directly interpreted if there is a single contaminant (or relatively consistent group of contaminants evaluated as TVOC) with a relatively constant challenge concentration. For multiple contaminants at multiple concentrations, judgment and experience are needed to interpret downstream measurements. Bayer et al. (2005) attempted to use single-component analyses to evaluate air cleaners in the field. That is, the up- and downstream samples were analyzed not for TVOC, but for particular chemicals (heptane, toluene, ethyl benzene, and formaldehyde). Bayer et al. found that the time variations in the challenge made the efficiency determinations so variable that the procedure could not be used reliably.

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CHAPTER 46

DESIGN AND APPLICATION OF CONTROLS

AUTOMATIC control of HVAC systems and equipment usually includes control of temperature, humidity, pressure, and flow rates of air and water. Automatic controls can sequence equipment operation to meet load requirements and to provide safe equipment operation using pneumatic, mechanical, electrical, electronic, and/or direct digital control (DDC) devices.

This chapter addresses control of typical HVAC systems, design of controls for system coordination and for energy conservation, and control system commissioning. Chapter 15 of the 2005 *ASHRAE Handbook—Fundamentals* covers details of component hardware and the basics of control.

SYSTEM TYPES

A pneumatic or electronic-based system has several physical control loops, with each loop including a combination of a sensor, controller, and actuator. DDC systems can more easily share a sensor value with several control loops or have multiple control loops selectively activate an actuator.

DDC systems allow information such as system status or alarms to be collected in a central operator workstation (OWS) and shared between HVAC systems, enabling advanced, energy-saving, system-level applications through a common communication protocol. ASHRAE *Guideline* 13 and *Standard* 135 have more detailed discussions of networking and interoperability.

Without a network and interoperability, DDC controllers are isolated: they collect information, but are unable to share that information across systems; they generate alarms, but are unable to display them at a central location where they can be more easily seen and addressed. In general, distributed processing locates local loop (e.g., variable-air-volume reheat coil) control near devices most immediately involved in that loop, and broader strategies (switching from heating to cooling) at a campus level, but applications can be located in any controller.

HEATING SYSTEMS

Heating systems include boilers, fired by either fuel combustion or electric resistance, direct flame-to-air furnaces, and electric resistance air heaters. Load affects the required rate of heat input to a heating system. The rate is controlled by cycling a fixed-intensity energy source on and off, or by modulating the intensity of the heating process. Flame cycling and modulation can be handled by the boiler control package, or the DDC can send commands to the boiler controls. The control designer decides under what circumstances to turn boilers on and off in sequence and, for hot-water boilers, at what temperature to control the boiler supply water.

Hot-Water and Steam Boilers

Hot-water distribution control includes temperature control at hot-water boilers or the converter, reset of heating water temperature, and control for multiple zones. Other controls to be considered

include (1) minimum water flow through boilers, (2) protecting boilers from temperature shock and condensation in the flue, and (3) coil low-temperature detection. If multiple or alternative heating sources (e.g., condenser heat recovery, solar storage) are used, the control strategy must also include a way to sequence hot-water sources or select the most economical source.

Figure 1 shows a system for load control of a gas or oil-fired boiler. Boiler safety controls usually include flame-failure, high-temperature, and other cutouts. Field-installed operating controls must allow safety controls to function in all modes of operation. Intermittent burner firing usually controls capacity, although burner modulation is common in larger systems. In most cases, the boiler is controlled to maintain a constant water temperature, although an outside air thermostat or other control strategies can reset the temperature if the boiler is not used for domestic water heating. A typical outside air reset schedule is shown in Figure 1. To minimize condensation of flue gases and boiler damage, water temperature should not be reset below that recommended by the manufacturer, typically 140°F, or condensation may occur and lead to corrosion-related failure. Condensing boilers are specifically designed to allow flue gases to condense, and can operate at lower water temperatures. Systems with sufficiently high pump operating costs can use variable-speed pump drives to reduce secondary pumping capacity to match the load and conserve energy. ASME (2004) requires that, for boilers above a certain size, a manually operated remote shutdown switch be located outside the boiler room door, to disconnect power to burner controls.

Hot-water heat exchangers or steam-to-water converters are sometimes used instead of boilers as hot-water generators. Converters typically do not include a control package; therefore, the engineer must design the control scheme. The schematic in Figure 2 can be used with either low-pressure steam or boiler water from 200 to 360°F. The supply water temperature sensor controls a modulating two-way valve in the steam (or hot-water) supply line. An outside temperature sensor usually resets the supply water temperature downward as load decreases, to improve the controllability of heating valves at low load and to reduce piping losses. This reset is typical for constant-flow systems; resetting the water temperature in variable-flow systems should be carefully studied, because it increases the pumping energy. A flow switch interlock should close the
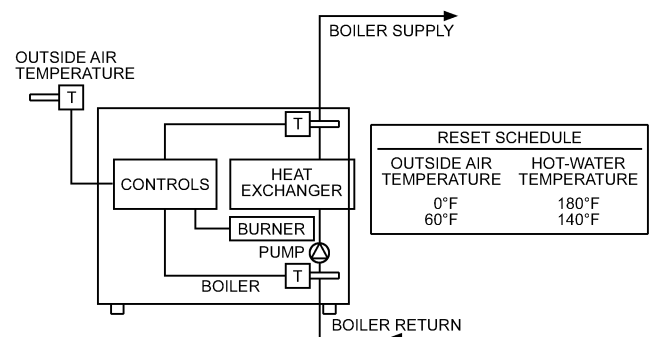
Fig. 1 Boiler Control
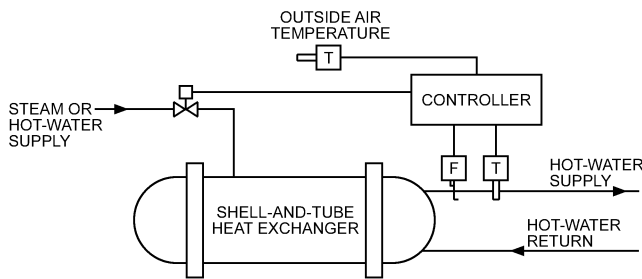
Fig. 2   Steam-to-Water Heat Exchanger Control
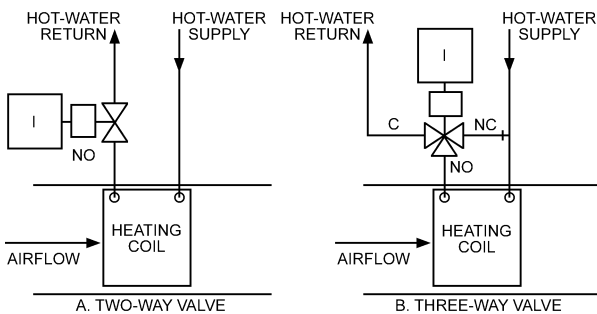
Fig. 3   Control of Hot-Water Coils

Fig. 4   Preheat with Face-and-Bypass Dampers

Fig. 5   Coil Pump Piped Primary/Secondary

two-way valve when the hot-water pump is not operating. Ensure that the flow switch will operate as expected at minimum flow rate on variable-flow systems. With an integrated DDC system, feedback from zone heating valves can be used to control starting and stopping of the hot-water pumps. On constant-flow systems, feedback can be used to reset the hot-water temperature to the lowest temperature that meets zone requirements. When shutting down a steam converter system, close the steam valves and allow the water to circulate for a while, to remove residual heat in the converter and prevent the pressure relief valve from opening.

Heating Coils

Heating coils that are not subject to freezing can be controlled by simple two- or three-way modulating valves (Figure 3). Steam-distributing coils are required to ensure proper steam coil control. (For information on air-side coils, see the section on Air Systems.) The modulating valve is controlled by coil discharge air temperature or by space temperature, depending on the HVAC system. In cold regions, valves are set to open to allow heating if control power fails. In many systems, the outside air temperature resets the heating discharge air controller.

To provide unoccupied heating or preoccupancy warm-up, a heating coil can be added to the central fan system. During warm-up or unoccupied periods, a constant supply-duct heating temperature is maintained and the cooling-coil valve is kept closed. Once the facility has attained the minimum required space temperature, the central air handler reverts back to occupied mode.

Heating coils in central air-handling units preheat, reheat, or heat, depending on the climate and the amount of minimum outside air needed.

Preheating coils using steam or hot water must have protection against freezing, unless (1) the minimum outside air quantity is small enough to keep the mixed air temperature above freezing and (2) enough mixing occurs to prevent stratification. Even when the average mixed-air temperature is above freezing, inadequate air mixing may allow freezing air to impinge on small areas of the coil, causing localized freezing. This blocks flow and, without a heat source, the rest of the coil and equipment downstream is at risk.
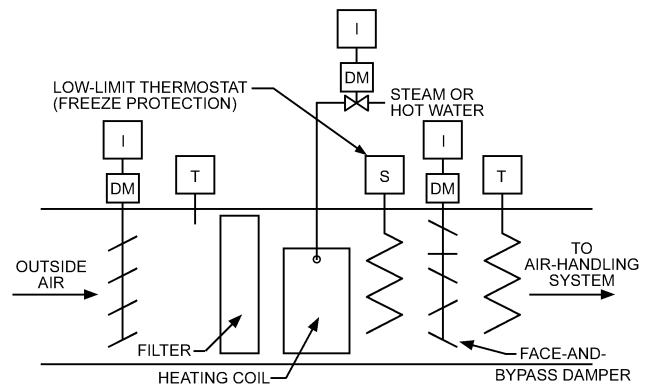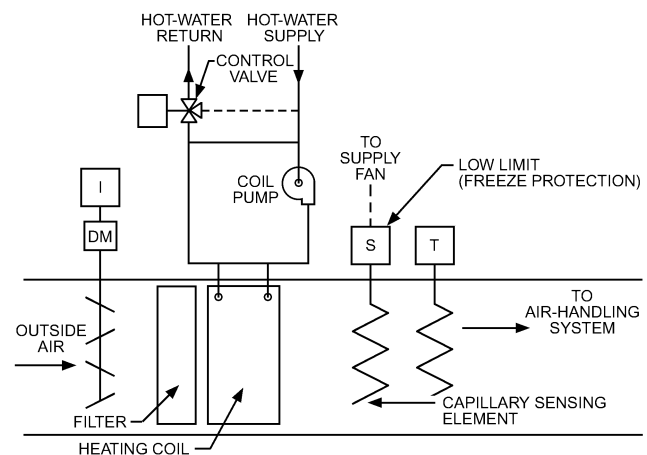
Steam preheat coils should have two-position valves and vacuum breakers to prevent condensate build-up in the coil. The valve should be fully open when outside (or mixed) air temperature is below freezing. This causes unacceptably high coil discharge temperatures at times, necessitating face-and-bypass dampers for final temperature control (Figure 4). The bypass damper should be sized to provide the same pressure drop at full bypass airflow as the combination of face damper and coil does at full airflow. When the outside air temperature is safely above freezing (roughly 35°F), the bypass damper is full open to the coil face and the coil valve can be modulated to improve controllability.

Hot-water coils must maintain a minimum water velocity in the tubes (on the order of 3 fps) to prevent freezing. A two-position valve combined with face and bypass dampers can be used (Figure 4), but a coil pump is more common. There are many coil pump piping schemes; the most common are shown in Figures 5 and 6. In each scheme, the control valve modulates to maintain the desired coil air discharge temperature and the pump maintains the minimum tube water velocity when the outside air is below freezing. Pumped coils can freeze, so additional low-temperature detection measures such as glycol-based fluids should be used in cold regions. Another protective device is a long, refrigerant-filled capillary tube used as a low-temperature sensing switch. If any short section of the tube is exposed to a low temperature (typically 38°F), it provides an alarm to shut the outside damper and open the return damper, or shut down the fan.

Figure 5 shows the conventional primary/secondary (or secondary/tertiary) arrangement where the coil pump and the pumps feeding the coil are hydraulically independent. It results in constant flow through the coil and in either variable flow through the
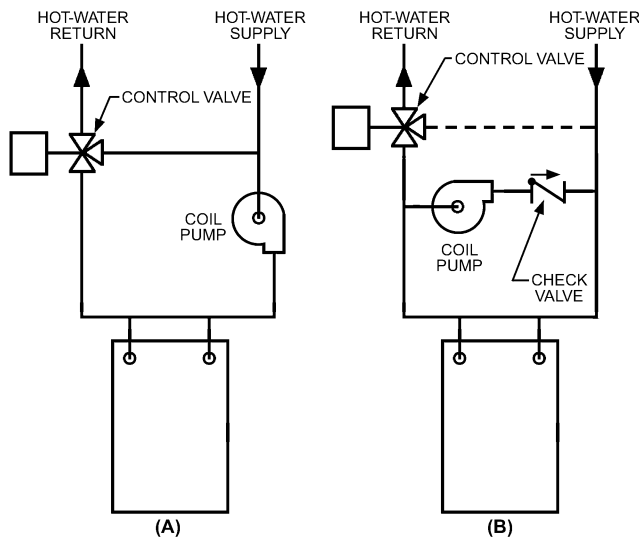
Fig. 6 Pumped Hot-Water Coil Variations: (A) In-Line and (B) Parallel

Fig. 7 Electric Heat: Solid-State Controller

Fig. 8 Duct Heater Control

primary loop, if a two-way valve is used, or in constant flow through the primary loop, if a three-way valve is used (shown dashed in the figure).

In Figure 6A, the coil pump is decoupled from the primary pumps by the bridge. This prevents the control and hydraulic problems that can be associated with series pumping. Flow to the coil is constant volume and flow to the system is variable (for a two-way valve) or constant (for a three-way valve). Pressure drop through the control valve is handled by the system pumps.

Figure 6B shows the coil pump piped in parallel with the primary pumps. This design has the advantage that hot-water flow can be achieved through the coil if either the primary pump or the coil pump fails. This design results in coil flow that varies from the pump design flow rate (when the control valve is closed) up through the sum of the pump flow rate plus the primary system flow rate (when the valve is wide open). Unlike the options in the previous two figures, the primary pump must be sized for the pressure drop through the coil at this high flow rate. This design also requires a little more care in selecting the heating coil and sizing the pipe entering and leaving the coil: at design conditions (when the pump is on and the control valve is wide open), flow through the coil significantly exceeds the design primary water flow. The entering water temperature is less than that of the entering primary water, and thus may require a larger coil heat transfer area (fin and/or rows). Flow through the primary circuit may be variable, if a two-way valve is used, or constant, if a three-way valve is used.

Some systems may use a glycol solution in combination with any of these methods; however, glycol affects control valve sizing (see Chapter 42 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*).

Electric heating coils (duct heaters) are controlled in either two-position or modulating mode. Two-position operation uses power relays with contacts sized to handle the amperage of the heating coil. Timed two-position control requires a timer and contactors. The timer can be electromechanical, but it is usually electronic and provides a time base of 1 to 5 min. Step controllers provide cam-operated sequencing control of up to 10 stages of electric heat. Each stage may require a contactor, depending on the step controller contact rating. Thermostat demand determines the percentage of on-time. Because rapid cycling of mechanical or mercury contactors can cause maintenance problems, solid-state controllers are preferred. These devices make cycling so rapid that control appears proportional; therefore, face-and-bypass dampers are not used. Use
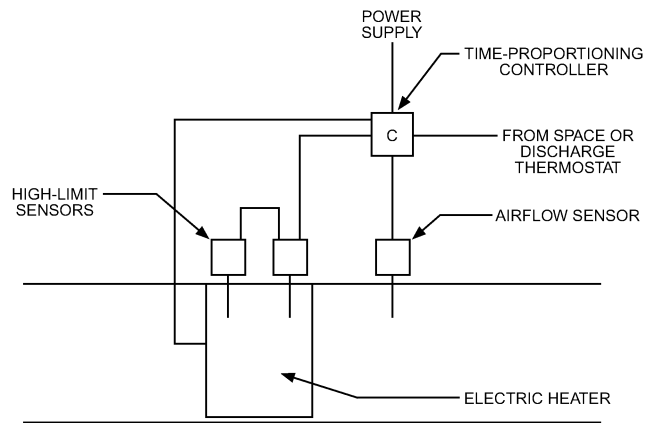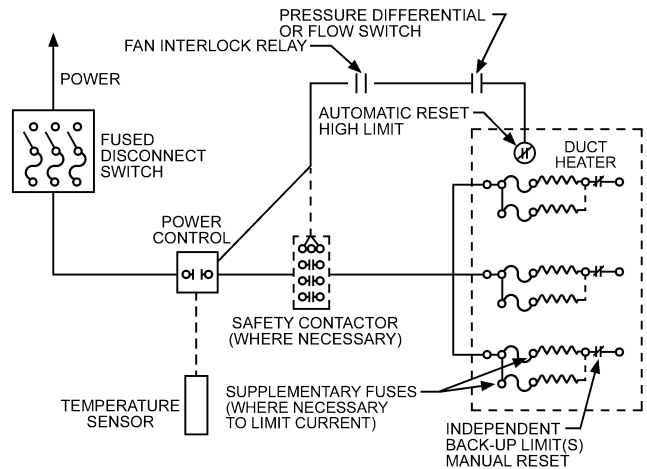
of electric heating coils is restricted in some areas because of energy consumption. Code compliance should be checked before using this application. A control system with a solid-state controller and safety controls is shown in Figure 7.

Current in individual elements of electric duct heaters is normally limited to a maximum safe value established by the *National Electrical Code*® (NFPA 2005) or local codes. Two safety devices in addition to the airflow interlock device are usually applied to duct heaters (Figure 8). The automatic reset high-limit thermostat normally turns off the control circuit. If the control circuit has an inherent time delay or uses solid-state switching devices, a separate safety contactor may be desirable. The manual reset back-up high-limit safety device is generally set independently to interrupt all current to the heater if other control devices fail. An electric heater must have a minimum airflow switch and two high-temperature limit sensors: one with manual reset and one with automatic reset. If still energized, electric coils and heaters can be damaged through overheating when air stops flowing around them. Therefore, control and power circuits must interlock with heat transfer devices (pumps and fans) to shut off electrical energy when the device shuts down. Flow or differential pressure switches may be used for this purpose; however, they should be calibrated to energize only when there is airflow. This precaution shuts off power if a fire damper closes or duct lining blocks the air passage. Limit thermostats should also be installed to turn off heaters when temperatures exceed safe operating levels.

Steam Coils. Modulating steam coils are controlled in much the same way as water coils. Control valve size and characteristics are important to achieve proper control (see Chapter 42 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*). Because the entering steam is hotter than the entering temperature of most water coils, a steam coil typically responds more rapidly than a comparable water coil. In low-temperature applications, two-position control should be used, as discussed previously.

Radiant Heating and Cooling

Radiation can be used either alone or to supplement another heat source. The control strategy depends on the function performed. For a radiation-only heating application, rooms are usually controlled individually; each radiator and convector is equipped with an automatic control valve. Depending on room size, one thermostat may control one valve or several valves in unison. The thermostat can be placed in the unit's return air or on a wall at occupant level; return air control is generally less accurate and results in wider space-temperature fluctuations. Unit-mounted thermostats and packaged controls allow lower component cost and better assembly surety, and avoid the cost and coordination of a second trade for remote sensor installation. When the space is controlled for the comfort of seated occupants, wall-mounted thermostats give the best results.

For supplemental heating applications, where perimeter radiation is used to offset perimeter heat losses (the zone or space load is handled separately by a zone air system), outside reset of the water temperature to the radiator should be considered. Radiation can be zoned by exposure, and the compensating outside sensor can be located to sense compensated inside (outside) temperature, solar load, or both.

Radiant panels combine controlled-temperature room surfaces with central air conditioning and ventilation. The radiant panel can be in the floor, walls, or ceiling. Panel temperature is maintained by circulating water or air, or by electric resistance. The central air system can be a basic one-zone, constant-temperature, constant-volume system, with the radiant panel operated by individual room control thermostats, or it can include some or all the features of dual-duct, reheat, multizone, or VAV systems, with the radiant panel operated as a one-zone, constant-temperature system. The one-zone radiant heating panel system is often operated from an outside temperature reset system to vary panel temperature as outside temperature varies. Where hydronic tubing or electric heating elements are imbedded in concrete, the rate of slab temperature change must be limited to prevent the concrete from cracking from thermal expansion.

Radiant panels for both heating and cooling require controls similar to those for a four-pipe heating/cooling fan coil. To prevent condensation, ventilation air supplied to the space during the cooling cycle should have a dew point below that of the radiant panel surface. The dew point should be actively controlled to prevent condensation; as internal latent loads increase, the chilled-water temperature for the radiant cooling panels should be reset upward if the dew point becomes too high.

Direct-Fired Gas Heat Makeup Air Units

Direct-fired gas heat makeup air units are controlled from either a two-position or modulating sensor/controller or thermostat. Control can be from discharge air temperature, space temperature, outside air temperature, or combinations of these (e.g., discharge control with space or outdoor temperature override or reset). Outdoor temperature may also be used to enable heating. Temperature set point can be fixed, or controlled by a manual adjustment or a time clock for night setback. Sometimes switches mounted on outside (overhead) doors are used either to turn the unit on or off or to change the set point to compensate for changes in heating load.

Units have manufacturer-supplied controls and safeties for flame proving, airflow proving, outside air temperature reset of gas flow, and discharge air low limit, and to meet the ANSI *Standard* Z83.4/

CSA *Standard* 3.7 combined safety standard. The manufacturer's controls either include temperature controls or provide an interface for the control contractor's temperature controls. Any added controls must not interfere with the manufacturer's controls and safeties.

When a line voltage space thermostat is provided, it must have an adequate volt-ampere rating for the total load it must carry. The amperage ratings of all relay coils, valve-solenoid coils, and other components should be totaled and the thermostat's rating matched to the total.

COOLING SYSTEMS

Chillers

The manufacturer almost always supplies chillers with an automatic control package installed. Control functions fall into two categories: capacity and safety.

Because of the wide variety of chiller types, sizes, drives, manufacturers, piping configurations, pumps, cooling towers, distribution systems, and loads, most central chiller plants, including their controls, are custom designed. In the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*, Chapter 38 describes various chillers (e.g., centrifugal, reciprocating, screw, and scroll), and Chapter 12 covers variations in various piping configurations and some associated control concepts. Chiller control strategies should always include an understanding of the chiller limits for minimum flow, minimum temperature, and acceptable rate of change for either.

Chiller plants are generally one of two types: variable flow (Figures 9 and 10) or constant flow (Figure 11). The figures show a parallel-flow piping configuration. Series-flow chiller configurations are often used in variable-primary-flow applications (Figure 9). The higher design water pressure drop of a series configuration is less of a concern in a variable-primary-flow application, because little time is spent at the maximum design flow operating condition.

Control of the remote load determines which type should be used. Throttling coil valves vary flow in response to load, and are used with variable-flow systems.

The decision to reset chilled-water temperature in a variable-primary-flow chiller system should be based on facility requirements. In some cases, the chilled-water set point should be reset to a lower rather than a higher temperature, because the fan and pump power savings may outweigh the additional chiller power consumption at a lower temperature. Chilled-water reset may not be appropriate in variable-flow systems with tight space temperature and humidity requirements, such as hospitals, computer data centers, museums, or some manufacturing facilities. These facilities should operate with a constant chilled-water supply temperature. In a variable-primary-flow system, when flow is below the chiller minimum and the bypass valve is open, the chilled-water temperature can be reset until system flow matches chiller minimum flow with
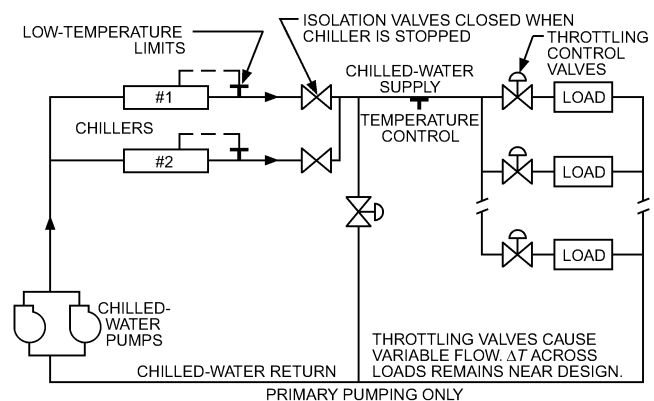
Fig. 9   Variable-Flow Chilled-Water System (Primary Only)

no additional pump power penalty. The chilled-water supply temperature typically establishes the base flow rate. To improve energy efficiency, the set point is reset for the zone with the greatest load (load reset) or other variances. Maintaining a high ΔT for the chillers improves plant efficiency. Properly sized coils and control valves help maintain a high ΔT.

The constant-flow system (Figure 11) is only constant flow under each combination of chillers on line; a major upset occurs whenever a chiller is turned on or off. The load reset function ensures that the zone with the largest load is satisfied, whereas supply or return water control treats average zone load. Use of constant-flow systems may be limited to smaller systems by energy codes. Three-way valves result in a lower ΔT at part load.

Chiller Plant Operation Optimization

Chapter 41 contains an extensive discussion on optimized control of chiller plants and a detailed description of the control strategies that can be applied. This section highlights the general conclusions that can be drawn from the specific optimization strategy in the section on Sequencing and Loading of Multiple Chillers of that chapter.

Additional chiller(s) should be sequenced on when the existing online chillers can no longer meet the required cooling load, which in practice is determined when the chilled-water temperature supplied to the cooling coils rises above its defined set point. When additional chiller capacity is required, the projected power of all valid chiller combinations with their associated chilled- and condenser water pumps should be evaluated and the chiller/pump combination with the least projected power should be selected to

operate. Valid chiller combinations involve chillers that are not in alarm or locked out, or have load ratios below a low limit (e.g., 30%) or above a high limit (e.g., 100%).

Multiple chillers should be operated at a point that minimizes overall plant power consumption, considering the power consumption of the auxiliary chilled- and condenser water pumps and cooling tower fans as well as of the chillers. For the general case of chillers with different part-load characteristics, multiple chillers should be operated at equal marginal coefficients of performance. That is, the ratio of the incremental change in thermal load to the incremental change in input power should be identical for each online chiller. For constant-speed-drive centrifugal chillers, sequencing is straightforward. It is best to run one chiller until fully loaded before bringing on a second machine. This dynamic changes for chillers with variable-speed drives, or if the chilled- or condenser water pumps are piped in a parallel (headered) arrangement or have variable-speed drives; for plants of this configuration, often overall plant power consumption is minimized when more chillers are operating at reduced load compared to fewer chillers operating at higher loads. In general, the optimal point of operation for each plant component (chillers, pumps, cooling tower fans, and air handler fans) that results in minimum plant power consumption occurs when each component is operating at equal marginal performance.

Chiller efficiency is a function of the percent of full load on the chiller and the difference in refrigerant pressure between the condenser and evaporator. In practice, the pressure is represented by condenser water exit temperature minus chilled-water supply temperature. To reduce the refrigerant pressure differential, the chilled-water supply temperature must be increased and/or the condenser water temperature decreased. An energy saving of 1 to 2% is obtained for each 1°F reduction in condenser water temperature supplied to a chiller. The savings are even greater when using variable-speed drives on centrifugal chillers.

The following methods are used to reduce the refrigerant pressure differential:

- Use chilled-water load reset to raise chilled-water supply set point as load decreases (use manufacturer's recommendations). Note that additional pump and fan power of VAV air handlers must be considered in calculating net energy savings.
- Lower condenser water temperature to lowest safe temperature (use manufacturer's recommendations), operate at full condenser water pump capacity, and maintain water temperature within design cooling tower approach (see Chapter 36 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*).

Because cooling tower performance is tightly coupled to chiller performance, the cooling tower fans should be controlled to minimize the sum of the chiller and tower power consumption. The section on Supervisory Control Strategies and Tools in Chapter 41 describes a near-optimal algorithm for optimizing control of the tower fans according to this criterion. In this algorithm, condenser water temperature is allowed to float between high and low limits, and tower fans are controlled according a mathematical formula involving the part-load ratio (normalized load) measured on the chilled-water side of the plant and design parameters from the cooling tower and chiller manufacturer.

Cooling Tower

The most common packaged mechanical-draft cooling towers for comfort air-conditioning applications are counterflow induced-draft and forced-draft. They are controlled similarly. The tower fans are typically controlled to maintain condenser water supply (CWS) temperature set point, as described previously. The CWS set point may be reset based on chiller load or, in the case of hydronic free cooling, space conditions.

Figure 12 shows a typical cooling tower control schematic.

Fig. 10   Variable-Flow Chilled-Water System (Primary/Secondary)
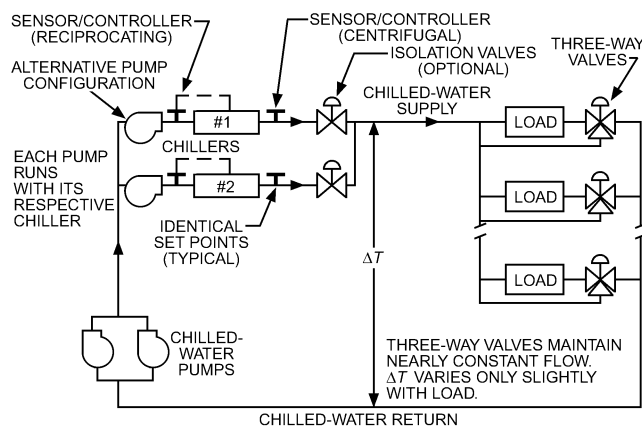
Fig. 11   Constant-Flow Chilled-Water System (Primary Only)

When the system includes large condenser water sumps, the temperature sensor's location must be considered. Large sumps introduce significant time delays into the system that must be accounted for. Often, condenser water supply piping does not run full at all times, particularly when draining to a sump. In this case, placing the temperature sensor so that is in contact with the water is important. This may necessitate locating the sensor on the bottom of an elbow or angled into the lower half of the pipe (to avoid mounting at the pipe bottom, where it could be susceptible to moisture collection).

On larger towers, two-speed motors or variable-speed drives can reduce fan power consumption at part-load conditions and stabilize condenser water temperature. Variable-speed drives (VSDs) improve control because fan speed can be better matched to the cooling load. When there are multiple towers in operation, each fan's speed should sequenced as follows.

Two-Speed Motors. The lowest fan speed should be used. For three two-speed towers, staging should be as follows:

Tower	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7
1	Off	Low	Low	Low	High	High	High
2	Off	Off	Low	Low	Low	High	High
3	Off	Off	Off	Low	Low	Low	High

Provisions should be made to decelerate the fan when switching from high to low speeds.

Variable-Speed Drives. All of the operating tower fans should operate at the same speed.

Tower fans should also have a vibration switch hard-wired to shut down the fan if excessive vibration is sensed.

Systems with multiple cooling towers may have isolation valves to allow unneeded towers to be shut down. When towers are piped on a common header, valves should be sequenced with condenser water pumps to ensure that pumps are not deadheaded or that flow to operating towers is not reduced below the manufacturer's minimum flow.

In climates where the wet-bulb temperature could be higher than the condenser water supply temperature (tower approach), a wet-bulb high limit should be provided so that the controls are not operating fans at increasingly higher speeds with no increase in cooling. This high limit is useful when using the towers on hydronic free cooling systems.
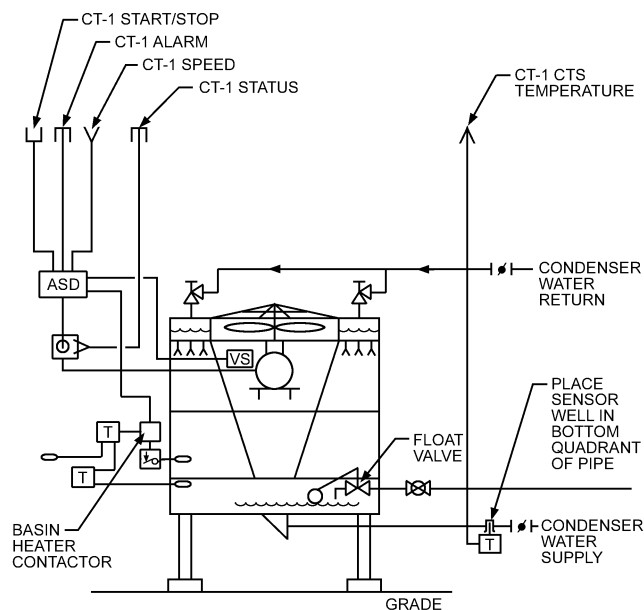
Most tower manufacturers do not recommend bypassing water around the tower as a normal temperature control function, because this causes localized drying of the tower media and spot scaling. Bypass valves may be required for some low-temperature operations or hydronic economizer operations. Check with the tower manufacturer for bypass valve applications.

Where year-round tower operation is required in cold regions, cooling towers may require sump heating and/or continuous full flow over the tower to prevent ice formation, and may also require deicing. The cooling tower sump thermostat controls an electric heating element or hot-water or steam valve to keep water in the sump from freezing. Typically, sump heating is locked out during tower operation and when outside air temperatures are above freezing. When operating the tower in cold weather, full water flow is needed to prevent localized ice formation. If towers build up ice, reversing the fan rotation and sending air backward through the tower can deice them, either manually or automatically. Many operating personnel prefer to do this operation manually so they can observe the towers while deicing is under way. If deicing cycles are needed, the fan starter or VSD must be able to reverse the fan direction. There should be deceleration time interlocks so that the fans spin to a stop before engaging reverse operation. Automatic deicing control strategies are available from tower manufacturers.

Auxiliary Control Functions. The control system may be required to cycle a fill valve to maintain sump level, or to monitor water consumption or water treatment systems. If the tower does not have sump heaters, the control system may be required to drain the tower and piping when outside air approaches freezing, and refill the tower on the next call for cooling.

Air-Cooled Chillers

Air-cooled chillers are controlled similarly to other chillers. If the chiller is to operate during cold weather, it must be equipped with a low-ambient kit. Typically this is a modulating damper that limits airflow across the condenser, usually provided as part of the chiller package. In very cold conditions, additional equipment is required. With variable-flow evaporators, careful attention to the manufacturer's recommended minimum flow must be observed. Flow in air-cooled chillers does not turn down as much as with other types of chillers. Minimum flow varies by manufacturer, but may be as high as 60%. Chilled-water supply temperature can be reset as described above. The chiller may be equipped with a barrel heater, usually controlled by the chiller's packaged controls, to prevent the evaporator from freezing in cold weather.

Water-Side Economizers

Water-side economizers are typically flat-plate heat exchangers where one side is cold tower water and the other side is chilled water. The heat exchanger prevents contamination of the chilled water by debris and chemicals found in tower water. The heat exchangers can be piped in series or in parallel. With parallel operation, the heat exchanger functions like another chiller. In series arrangement, the heat exchanger precools the chilled-water return to the chillers. When there is enough heat exchanger capacity, the chillers may be turned off and a bypass opened to direct flow around the chillers. Chilled-water temperature is controlled by varying the tower fan speed. When changing from water-side economizer mode to chiller mode, the condenser water is cold, which often makes starting the chiller difficult. Consult the chiller manufacturer for the requirements of each specific machine. To maintain condenser head pressure, many manufacturers recommend self-contained modulating valves or control valves modulated by the DDC system. When modulating the condenser water flow to maintain head pressure, the flow switch may need to be bypassed for a short time to keep the machine operating; consult the manufacturer. The pressure signal used for modulating the valve should be directly from a pressure transmitter. Relying on pressures obtained from the chiller controller

CT-1 START/STOP
CT-1 ALARM
CT-1 SPEED
CT-1 STATUS
CT-1 CTS TEMPERATURE
ASD
CONDENSER WATER RETURN
VS
PLACE SENSOR WELL IN BOTTOM QUADRANT OF PIPE
FLOAT VALVE
BASIN HEATER CONTACTOR
CONDENSER WATER SUPPLY
GRADE

Fig. 12   Cooling Tower

through the network makes for difficult control, because data refresh rates may not be sufficient. Another challenge in modulating chiller valves is valve sizing. If line-sized valves are used, they are oversized for good control. Valves correctly sized for control add a considerable pressure drop to the condenser water loop.

Cooling Coil

Chilled-water or brine (glycol) cooling coils are controlled by two- or three-way valves (Figure 13). These valves are similar to those used for heating control, but are usually closed to prevent cooling when the fan is off. The valve typically modulates to maintain discharge temperature or space temperature set point.

Direct-expansion (DX) cooling equipment is usually controlled by an air, space, or coil discharge temperature feedback loop in discrete stages, by starting and stopping compressors and by applying mechanical unloaders or hot-gas bypass valves. Most DX systems for commercial application have two to six stages.

Most often, these feedback loops are set up to cycle the cooling stages on and off as air temperature swings up and down around the set point. Depending on the capacity of the stages and the allowable error in the feedback loop, it is sometimes possible to set up the loop so that it stabilizes (rather than cycling), with some number of stages active and a steady-state temperature error.

When set up properly, a cycling DX system under a steady load operates like a two-position control loop (see Chapter 15 of the 2005 *ASHRAE Handbook—Fundamentals*). Some stages run steadily, and one stage cycles on and off. The behavior of the closed loop can be described by the cycling rate and corresponding swing in controlled air temperature. Most DDC algorithms for DX control address both temperature control (e.g., set points, feedback gains, staging dead bands) and equipment cycling restriction (e.g., minimum-on timer, minimum-off timer, interstage delay.) These two characteristics are inextricably linked by thermal sizing and loading conditions. Either characteristic can be affected by adjusting the control algorithm, but is not possible to affect both characteristics independently: any reduction in temperature swing is accompanied by an increase in cycling rate. Overtightening temperature control will conflict with cycle controls and be rendered irrelevant.

When set up improperly, a DX system may cycle through multiple stages as the temperature oscillates around the set point, rather than having only one stage cycle on and off. Compared to proper operation, both the cycle rate and temperature swing are excessive. This operation can usually be corrected by adjusting parameters in the feedback algorithm.

Some staging systems are arranged so that it takes a greater temperature error to activate the higher stages. The result is that, at higher loads, the system operates at higher temperatures. This is usually not desired; it is usually intended that the system operate in the same temperature range, regardless of loading on the stages. This can be accomplished in many ways, including a proportional-plus-integral (PI) controller driving a staging module.
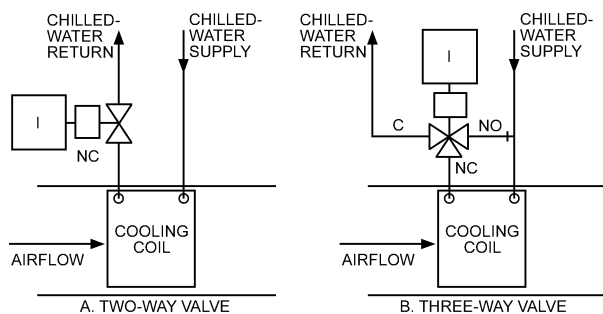
If the DX system serves a single zone, the feedback signal is usually the space temperature, which usually varies by 1 to 4°F. If the DX equipment serves multiple zones, as in a VAV air handler, the feedback signal is often the coil discharge temperature. Measured at this point, temperature swings appear much larger, though the effect on zone comfort is the same. When adjusting or specifying a DX system for discharge temperature control, it is important to allow the wider range of temperatures.

AIR SYSTEMS

Variable Air Volume (VAV)

Supply Fan Control. Most VAV systems have pressure-independent terminals, which means a separate airflow control loop operates each terminal damper. In normal operation, these loops combine to set the airflow though the supply fan. So, within limits, the fan controller has no effect on airflow to the zones. The VAV fan controller

- Ensures the pressure in the duct is enough to serve the terminals
- Prevents excessive pressure disrupting the terminal flow loops
- Avoids unnecessary energy consumption at the fan
- Keeps the fan in a stable region of the pressure-flow curve

Historically, a variety of mechanisms (e.g., bypass damper, movable inlet vanes) have been used to regulate fan output. These methods vary widely in efficiency and energy consumption. A bypass damper (Figure 14), for example, does not change the fan's output, but can allow the fan to accommodate distribution system flow variations without fan instability. Some methods, such as discharge dampers, are restricted by energy codes. Variable-speed drives (VSDs) are frequently used because their low energy consumption and falling first cost makes them cost effective.

The most common variable-airflow method is a closed-loop proportional-with-integral (PI) control, using the pressure measured at a selected point in the duct system. Most often, the set point is a constant, selected by the designer and confirmed by the balancer during system commissioning. If the pressure loop and flow loops are sufficiently decoupled, this is a solid, stable design. However, this control strategy is based on the readings of a single sensor that is assumed to represent the pressure available to all VAV boxes. Choosing duct pressure sensor location can be difficult: if it malfunctions or is placed in a nonrepresentative location, operating problems will result; if it is located too close to the fan, the sensor will not sufficiently indicate service of the terminals. This usually leads to excessive energy consumption. Some have reported that placing the sensor at the far end of the duct system couples fan control too closely with the action of a single terminal, making it difficult to stabilize the system. Experience indicates that performance is satisfactory when the sensor is located at 75 to 100% of the distance from the first to the most remote terminal (Figure 15).

Though widely used, this fixed-pressure design uses more energy than necessary. Even when applied carefully, there are many

Fig. 13 Control of Chilled-Water Coils
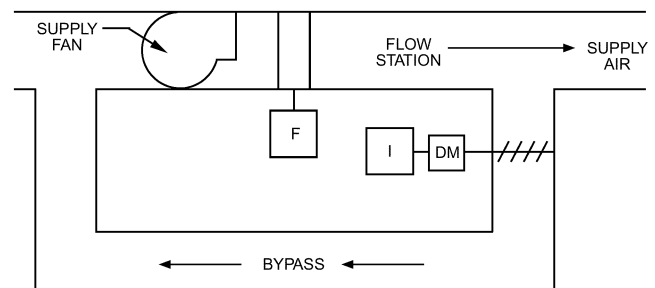
Fig. 14 Fan Bypass Control to Prevent Supply Fan Instability

operating hours when the fan pushes air through a system full of partly closed dampers. Many building codes and ASHRAE *Standard* 90.1 require automatically adjusting duct pressure based on zone requirements as system load varies. Airflow to zones is still regulated by flow loops in the terminal controllers and is unaffected, but the system meets the load more efficiently with terminal dampers closer to open and a lower fan speed. This reduces energy consumption at the fan. Ideally, pressure is reduced to the point that some of the dampers open all the way. Any further supply fan speed reduction reduces airflow at the terminals.

Many methods have been published to automatically reset duct pressure (Ahmed 2001; CEC 2003; Englander and Norford 1992). Reported energy savings, monitored over weeks or months, have ranged from 30 to 50% of fan energy used by the same system running with a constant-pressure set point. All of these reset designs use data from terminal controllers to alter fan operation.

Most reset strategies use zone control data to adjust the set point of the duct pressure control loop. This makes the location of the pressure sensor much less important. In many cases, it makes the most sense to measure duct pressure near the fan outlet.

Other reset strategies (Hartman 1993) eliminate the pressure control loop, using data from zones to drive the fan directly.

Reset strategies may be categorized according to the type of data collected from the terminal controllers. At least three approaches are in commercial use. The terminal controllers may deliver

- Damper position (or damper position and flow error)
- Flow set point
- Saturation signal (terminal indicates that the pressure is insufficient)

Data available for coordinating a fan control system vary with model of terminal controller. Most have both a flow set point and a damper position value, though the suitability of the data for coordination varies. Many controllers do not have saturation signals, but they have become more common since they were added to the LONMARK profile (LONMARK 2002). Control system designers should ensure that data available from terminal controllers, the fan control strategy, and network data capacity are compatible.

The signal selected for coordination can determine the data communication load that the fan control strategy places on the network. Flow set points and saturation signals tend to change less often than damper position or flow measurements, so using them is more practical, especially in systems with many terminals. Saturation signals are binary, so they do not indicate their distance from the critical point. This can affect reset algorithm design.
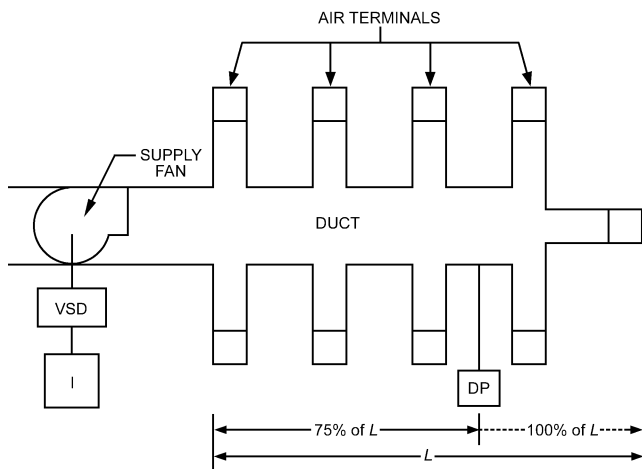
One approach (using **damper position data**) is based on the idea that the desired mechanical operating point occurs when at least one damper is fully (or almost fully) open, and all terminals deliver the required flow. The fan controller processes damper position data from each terminal and adjusts duct pressure (or fan speed) to drive one damper open. To ensure that the open box is not starved, the reference may be set a little lower (95% open, for example), or the controller may check flow (or flow error) data from the terminal controllers. Some terminal controllers do not always have reliable values for the damper position because of the way they apply floating actuators. It is important to take this into account when selecting a reset method.

Another approach (using **flow set points**) is based on the fact that the required pressure depends on the distribution system (ducts, terminals, diffusers) and required flow. One way is to add the flow set points from each terminal and then use an empirically determined function to set the pressure. A more exact approach puts the individual flow set points into a calibrated model of the duct network, and calculates the pressure needed at fan discharge to drive the required flow to each terminal (Kalore et al. 2003). This online optimization applies the same calculations used to size a fan in real time. The pressure control loop then adjusts the fan speed to maintain the calculated pressure, which results in all terminals being satisfied, with one critical damper fully open (Ahmed 2001, 2002). This method is now in commercial use. In contrast to a reset based on damper position or saturation signals, a reset based on flow set point is open loop; this means that performance depends on careful calibration, but is inherently stable.

A third approach (using a **saturation signal**) distributes more of the logic. Each terminal controller uses flow data, damper position data, timing, or other information to decide whether its local loop is sufficiently supplied by the fan. If not, the saturation signal is activated. If a saturation signal is available, then the fan control algorithm depends less on the details of the terminal control than other methods. These signals are typically mated with a fan algorithm that ramps pressure up or down according to the number of unsatisfied terminals.

To specify a pressure reset system, a designer can select the fan control algorithm, data that integrate terminal controllers, and characteristics of the communication network. Alternatively, the designer can specify that the intended mechanical operating point is the lowest pressure that satisfies the terminals. Verifying this condition is fairly straightforward for commissioning agents or building operators. A mechanically specified system allows proposals from vendors with a wider variety of equipment and algorithms.

Supply fan warm-up control for systems having a return fan (Figure 16) must prevent the supply fan from delivering more airflow than the return fan maximum capacity during warm-up mode. If pressure on fan discharge goes negative, supply fan speed should be reduced.

Duct Static Pressure Limit Control. In larger fan systems, or where fire or fire/smoke dampers could close off a significant percentage of airflow, static pressure limit controls are recommended. When the high limit set point is reached (low limit on the suction side of the fans), the fan is deenergized. Limit controls should be manually reset. On large fans, inertia of the fan wheel could damage the ductwork even after the fan is deenergized. Additional protection for the ductwork (e.g., mechanical relief dampers) is needed in these situations.

Space Pressure Control. Differential static-pressure control, differential airflow, and directional bleed airflow are methods used to pressurize a space relative to adjacent spaces or the outside. Typical applications include pressure barriers for any occupied space to maintain interior comfort conditions, to prevent infiltration of moisture unfiltered and untreated air. Applications requiring higher-performance controls include cleanrooms (positive pressure to prevent infiltration; see Chapter 16), laboratories and health care

Fig. 15   Duct Static-Pressure Control
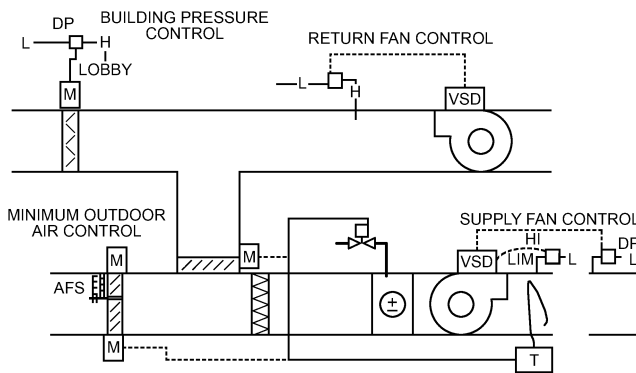
Fig. 16   Supply/Return Fan Control
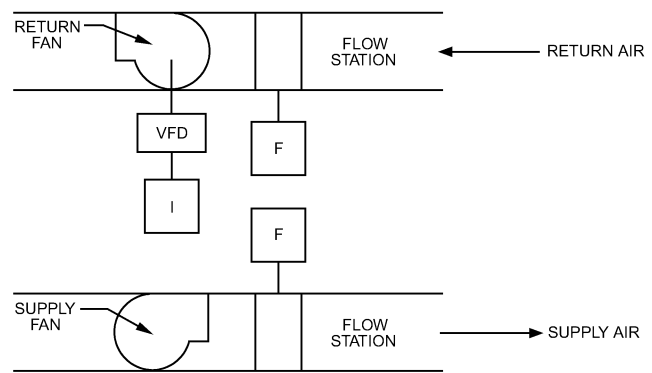
Fig. 17   Airflow Tracking Control

infection control (positive or negative, depending on use; see Chapter 7), and various manufacturing processes, such as spray-painting rooms (see Chapters 29 and 30 for industrial applications). The pressure controller usually modulates fan speed or dampers to maintain the desired pressure relationship or bleed airflow direction as exhaust volumes change. An alternative is to supply sufficient makeup air and to modulate a separate exhaust system to maintain space pressurization flow as auxiliary exhausts in the space are turned on or off.

Health Care Pressurization Codes, Regulations, and Application Design Guides. Health care spaces have specific pressure control guidelines for minimum air change rates, differential pressure, flow, or leakage rates. States typically adopt standards for HVAC system design, ventilation, filtration, and pressurization to ensure an adequate environment for health care occupancies. These standards and their application are discussed by the American Institute of Architects (AIA 2001), ASHRAE (2003a), and Chapter 7. The Joint Commission on Accreditation of Healthcare Organizations (JCAHO) also enforces HVAC system design and construction standards listed in the AIA guidelines.

In addition to these regulations, standards and guidelines published by ASHRAE, the AIA, American Society of Hospital Engineers (ASHE), Centers for Disease Control and Prevention (CDC), National Institute of Health (NIH), and National Institute of Occupational Safety and Health (NIOSH) define the expectation of care and services in health care.

Most guidelines do not allow spaces to be used for purposes that require pressurization flow to change directions (e.g., positive to negative flow), even if the space and control components are able to perform the change.

Building Pressurization. Building pressure and outside airflow control must be integrated for proper system performance. Pressure results from the development of a pressurization flow between adjacent pressure zones. A zone is positive to an adjacent zone if the pressurization flow across the zone barrier is positive. Generally, outside air is required to pressurize a zone.

Static pressure control is one method for control of the relief or exhaust fan requiring direct measurement of the space and outside static pressures. The location for measuring inside static pressure must be selected carefully, away from openings to the outside or elevator lobbies, and, when using a sensor, in a large representative area that is shielded from wind pressure effects or drafts. The outside location must also be selected carefully, typically 10 to 15 ft above the building and oriented to minimize wind effects from all directions.

The amount of minimum outside air varies with building permeability and relief or exhaust fan operation. Control of building pressurization can affect the amount of outside air entering the building.

Return or relief fan control for VAV systems is required for proper building pressurization and minimum outside air control. The return fan is controlled to maintain the return air plenum pres-

sure. The relief fan or exhaust air damper may be controlled to maintain building static pressure (see Figure 16).

Direct-measurement pressurization flow compares an interior static pressure location to an outdoor reference to modulate fan speed. This control allows for greater operational repeatability, greater comfort control, improved energy savings potential and the opportunity to use a small (0.004 in. of water) differential counterflow barrier to the infiltration of moisture that can cause condensation and mold in exterior walls.

Indirect building pressure control uses duct or fan airflow measurements to control a fixed differential air volume by modulating dampers, fan speed or discharge rates (Figure 17). Because return air is typically the controlled variable and because its rate is set to track the normal changes in VAV supply at a fixed rate, this method is referred to as return fan or airflow tracking. The airflow differentials that may be tracked are described in the following pressurization flow model, which proves the equivalency between the differentials of air system flows (intake minus exhaust, or supply minus return, assuming that positive pressurization flow is desired).

Fixed-differential air volume to maintain pressurization flow, rather than measured space static pressure, results in very stable control for several reasons. First, multiple air-handling systems operate independently. Systems based on measured static pressure generally interact with each other in such a way that it is impossible for each fan system to operate independently. As a result, pressurization problems in specific pressure zones are likely. Second, static pressure control can only ensure that pressure is maintained at the measured location and as compared to a reference point. The reference selected may not represent a true neutral position for external static. Finally, transient changes in the building (e.g., doors opening, wind gusts) result in the system going out of control in a static pressure-based system.

Indirect building pressure control, as an independent control loop, avoids system instability and inefficiencies when doors open or close, and when transient environmental changes affect differential pressure and would otherwise cause wide swings in volumetric relationships.

Airflow quantity is indicated in Figure 18 by Q. Q_P is leakage in or out of the room, driven by the net pressure differential. Note that each surface may have a different ΔP because this value is relative to the pressure in the space on the other side of the wall. The windward wall may have significant infiltration, whereas the door into a very negative infectious isolation room may show exfiltration from the room being measured.

Pressurization flow can be controlled using airflow tracking by maintaining a fixed-volume differential between either total intake and total exhaust, or total supply and total return. Unfortunately, the more direct method of control is usually not practical because of the difficulty in measuring flow rates with most exhaust/relief configurations. Intake airflow rates may be measured reliably

BUILDING

BUILDING PRESSURE MODEL: $Q_P = Q_{OA} - Q_{EX}$

MATHEMATICAL EQUIVALENT: $Q_{Rec} + Q_{OA} = Q_{SA}$
$Q_{Rec} + Q_{EX} = Q_{RA}$
$Q_{OA} - Q_{EX} = Q_{SA} - Q_{RA}$
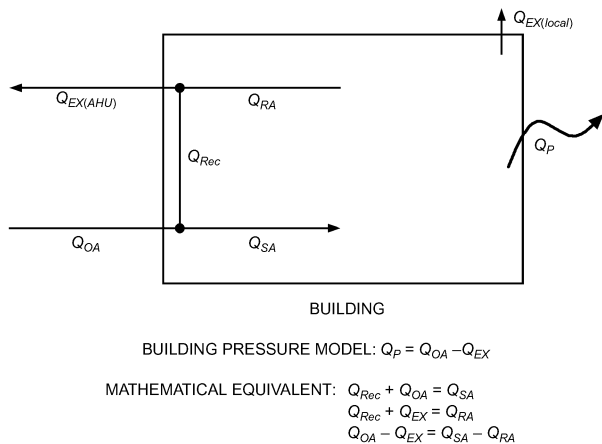
Fig. 18　Building Pressure Model

upstream of modulating intake dampers and with minimal protection from external wind effects, or by reducing the intake duct size sufficiently to overcome the low-velocity limits of differential-pressure-based sensors.

When the control strategy changes from occupied (ventilation air required) to unoccupied warm-up, which does not require ventilation but needs thermal control to change the air-balancing requirements, warm-up is accomplished by setting return airflow equal to or just slightly less then the supply fan airflow, with toilet and other exhaust fans turned off and limiting supply fan volume to return fan capability. If exhaust fans remain running, then the supply fan must deliver sufficient outside air to make up the exhaust and still have a slightly pressurized space. During night cooldown, when using large quantities of outside air, the return fan operates in the normal mode (Kettler 1995).

VAV systems that use return or relief fans require control of airflow through the return or relief air duct systems. Return fans are commonly used in VAV systems when return duct pressure loss is high, and a high percentage of outdoor air is used (Kettler 2004). In a return fan VAV system, there is significant potential for control system instability because of the interaction of control variables (Avery 1992; Kettler 2004), which typically include supply fan speed, supply duct static pressure, return fan speed, mixed air temperature, outside and return air damper flow characteristics, and wind pressure effect on the relief louver. Interaction of these variables and selection of control schemes to minimize or eliminate interaction must be considered carefully. Mixed-air damper sizing and selection are particularly important. Zone pressurization, building construction, and outside wind velocity must be considered. The resultant design helps ensure proper air distribution, especially through the return air duct.

Unstable fan operation in VAV systems can usually be avoided by proper fan sizing. However, if airflow reduction is large (typically over 60%), fan sequencing is usually required to maintain airflow in the fan's stable range.

Supply air temperature reset can be used to avoid fan instability by resetting the cooling coil discharge temperature higher (Figure 19), so building cooling loads require greater airflow. Because of the time lag between temperature reset and demand for more airflow, the value at which reset starts should be selected on the safe side of the fan instability point. When this technique is used, it must be ascertained that zone cooling load and dehumidification requirements can be met with the higher discharge air temperature. Discharge temperature should be reset lower to keep fan speed at the lowest acceptable value for stability. This saves fan power, and only decreases chiller efficiency a small amount.
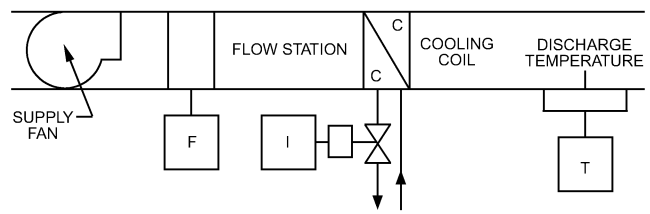
Fig. 19　Coil Reset Control to Prevent Supply Fan Instability
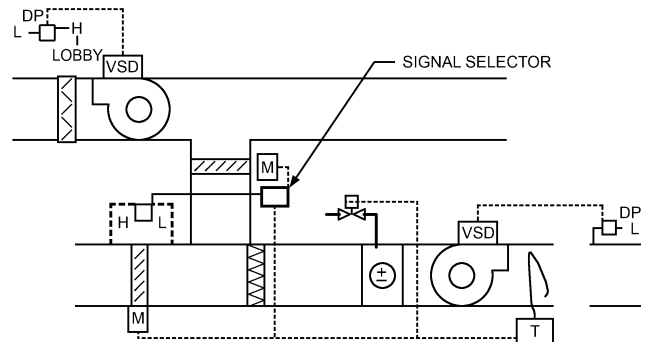
Fig. 20　Minimum Outside Air Control Using Differential Pressure Controls
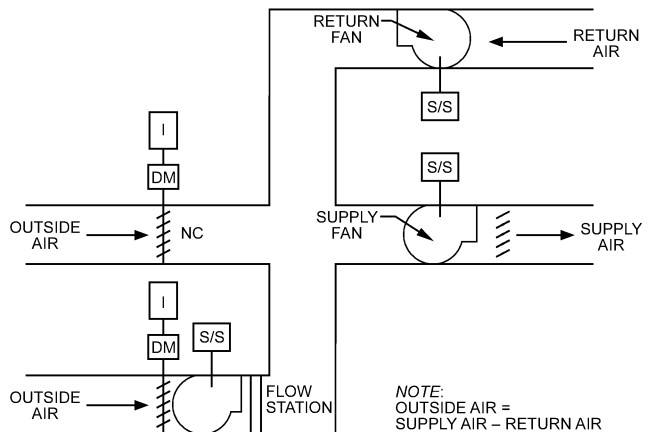
Fig. 21　Minimum Outside Air Control with Outside Air Injection Fan

Minimum Outside Air Control. Fixed minimum outside air control provides dilution air for ventilation, pressurization flow (usually exfiltration), combustion air for processes converting fuel to heat, and makeup air for exhaust fans.

Several variations of minimum outside air control for VAV systems are possible:

- Minimum outside airflow may be determined by measuring intake airflow directly upstream of the outside damper and modulating the return damper to maintain target minimum flow rate as supply airflow is reduced (Figure 20).
- A dedicated outdoor air injection fan may be used (Figure 21).
- An airflow station may be installed in the minimum outside air section and minimum flow rate controlled directly by modulating the intake and return dampers (or return fan) in sequence (Figure 22). In this case, the intake opening should be sized for velocities high enough to facilitate measurement and avoid wind effects, yet low enough to prevent moisture entrainment.

MINIMUM OUTDOOR AIRFLOW MEASUREMENT

TOTAL OUTDOOR AIRFLOW MEASUREMENT USING STAGED AIRFLOW STATIONS
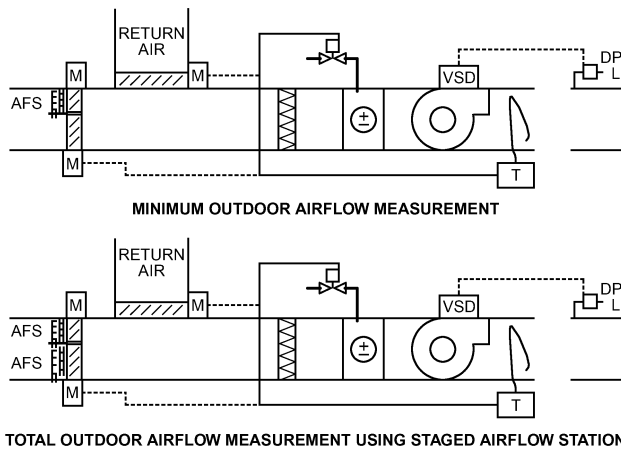
Fig. 22 Outside Air Control with Airflow Measuring Stations

According to the *Standard 62.1 User's Manual* (ASHRAE 2005), most VAV systems require outdoor airflow sensors and modulating dampers or injection fans for compliance; a fixed-speed outdoor-air fan without control devices will not maintain rates within the required accuracy. In addition, ASHRAE *Research Project* RP-980 (Krarti et al. 2000) and the *Standard 62.1 User's Manual* suggest that even small errors in measurements of total supply airflow and total return flow can cause significant errors in the determination and control of the minimum outside airflow rates, making return fan or airflow tracking unsatisfactory for minimum outside ventilation control. Dynamic intake controls require real-time feedback of intake rate changes for accurate system adjustments.

If the total outdoor airflow range of a VAV design from a minimum of less than 50% to maximum design capacity is to be measured, the selected measurement technology should provide the needed reliability across the entire anticipated temperature and velocity range. One method for accomplishing this with pitot arrays is by subdividing the intake and using dual airflow stations sized for 1/4 and 3/4, or 1/3 and 2/3 of the maximum opening size. This increases the velocity pressure for the pitot array to ensure accurate measurement at minimum pressure drop (Kettler 2000). If more outside air is supplied than the difference between the supply and return fan airflows, a variation of economizer cycle control may be used (Figure 22).

In addition to the capability of lower flow rate measurement, significant consideration should be given to the modulating mechanism's ability to control rates as low as those anticipated. Today's rooftop air-handling units with economizers usually use a single large damper to control both economizer and minimum air intake rates. This single damper must then control at minimum air velocities (often below 50 fpm) under maximum turndown conditions. Traditional damper blade and linkage designs combined with the finite modulating capabilities of actuation devices make stable control flow difficult at these rates. The resistance of the wide-open damper can be expressed as a fraction of the total system resistance, called **damper authority** or **characteristic ratio** (Lizardos and Elantz 2000). Both damper authority and measurement placement in relation to the exterior wall should be evaluated and determined when control of intake flow rates below 200 fpm is required.

In systems using 100% outside air, all air goes to the fan and no air is returned (Figure 23). The outside air damper is interlocked and usually opens before the fan starts. Fan speed may be controlled to dynamically compensate for internal or external environmental conditions that affect mixed air plenum pressure and fan performance, or to compensate for filter loading when constant supply volume is required.
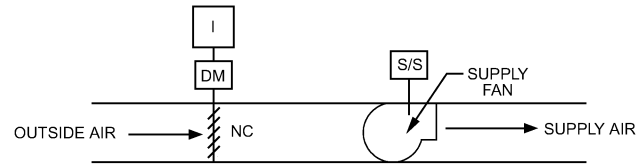
Fig. 23 100% Outside Air Control

Regardless of the type of system, pressurization flow rate and outside airflow rate are controlled similarly. There is generally no relief at the air-handling unit during minimum outside air mode.

The outside airflow set point for dilution ventilation should be established using ASHRAE *Standard* 62.1. In addition, the outside air set point for pressurization should be established by adding the pressurization flow requirement to the sum of the local exhausts in the zones served by the air-handling system. The greater of the two dictates the outside air set point. If the outside airflow rate for minimum ventilation significantly exceeds that required for pressurization, the economizer control strategy for pressurization control should be followed.

Because wind and stack pressure variations can significantly affect intake flow rates, outside airflow should be actively controlled on all systems, regardless of type (VAV, constant-volume, etc.). The most practical way to maintain outside air intake flow rate is to install a permanently mounted airflow measurement device properly selected for use in outside air intakes.

Traditionally, the outside air damper is modulated or the outside air and recirculation dampers are modulated inversely to maintain set point. Unfortunately, most dampers are oversized and are ineffective as control valves, often preventing stable control.

A more reliable approach is to decouple the outside air and recirculation dampers by individually actuating each. Depending on the system, the outside airflow rate is then controlled by sequencing the dampers. An effective sequence sets the outside air damper to a fixed minimum position. The damper is opened if the set point is above the measured airflow rate. Once the outside air damper is fully opened, the recirculation damper begins to close. The return fan (if present) can also be used to maintain outside air set point.

This sequential control strategy improves performance of oversized dampers and allows the use of opposed-blade dampers. If the selected airflow measuring devices can measure low airflows (down to 150 fpm), a single outside air damper can be used on systems with air-side economizer sections, thus simplifying control. Otherwise, a separate minimum outside air damper must be installed.

Dynamic Reset of Intake Rates or Demand-Controlled Ventilation (DCV). Codes and standards address the need to maximize the efficiency of operational energy usage. One area that has received recent attention is minimizing the amount of required intake air when spaces being served have less than maximum occupancy. Other reasons for resetting intake rates include operational changes, environmental changes, and technical compliance.

To effect this type of control and to comply with provisions of codes and standards, the intake rate must be controlled to a specific minimum level for full occupancy and adjusted based on a real-time input that reflects changes in occupancy.

DCV's operational control effectiveness largely depends on the reliability of the individual sensor inputs. The appendix on CO_2-based DCV in the *Standard 62.1 User's Manual* (ASHRAE 2005) illustrates this point.

Because of the direct relationship to occupancy, intake rates may be expressed in flow rate per person for the human or odor component of the intake requirement. Until recently, this relationship was thought to allow several variations of a CO_2 concentration balance formula to be used to calculate the effective occupancy intake requirement based on several prerequisite assumptions during steady-state conditions; research has indicated that this approach may not

be accurate or reliable enough for compliance with existing rate-based codes.

The most obvious solution is to use direct counting instruments or systems that provide HVAC controls with a net count of occupants per zone served by or controlled by a specific air-handling unit (AHU). This configuration allows software in the system to dynamically adjust the intake rate at the AHU based on direct feedback of both the demand (changing occupancy level) for control and the ventilation rate (at the intake and supply to the zone).

There are alternatives to direct counting. All of them have serious uncertainties, but none very different from those of more traditional CO_2-based DCV. With these alternatives, ASHRAE *Standard* 62.1's original intention of dynamic reset (i.e., continuously determine intake rate and reset it) can be satisfied based on a known or calculated population.

In recognition of the significance of building-generated contaminants, ASHRAE and international ventilation standards include requirements to reflect both components used to determine minimum ventilation rates: people, and contaminants generated in the space that they occupy. Now, using CO_2 sensing for ventilation control becomes more complicated, because the total requirement has a volume/area component that does not vary with changes in occupancy.

Designers should use caution when implementing demand-based ventilation schemes that reduce outside air without provisions for ensuring that pressurization flow is maintained (i.e., the relationship between the outside air and the exhaust air is maintained). When outside air dew point approaches or exceeds 60°F, it is essential to create a net positive pressurization flow to prevent transport of water and outdoor air contaminants into the building or its envelope. Excessive moisture can result in mold growth, structure damage, and poor indoor air quality. Net positive pressure can dry the building envelope and help ensure proper temperature and humidity control within the building. The concept of net pressure must be understood for building systems. Wind pressure acting on the exposed building surfaces cannot be overcome with the mechanical system without damaging envelope integrity. Therefore, a net positive pressure is the best scenario that can be maintained. As a result, even a properly pressurized building can have exterior walls improperly pressurized for short periods of time. When outside air temperature is less than indoor air dew point, a net neutral pressurization flow should be maintained.

The potential energy savings from minimizing intake rates through demand-controlled ventilation must be weighed against the probability that control errors will overcome and negate the estimated savings, making the risks of underventilation and depressurization the larger consideration.

Air-Side Economizer Cycle. Economizer-cycle control reduces cooling costs when outside air is cool and dry enough to be used as a cooling medium. If outside air is below an economizer changeover temperature limit, typically 65°F (selected to represent outside air with a mean coincident dew point below 60°F), the return, exhaust, and outside air dampers modulate to maintain a mixed-air cooling set point, typically 55 to 60°F (Figure 24). The outside and exhaust dampers would be fully or mostly open and would close, and the return air dampers open, when the supply fan is not operating. When the outside air temperature exceeds the economizer changeover temperature limit set point, the outside air damper closes to a fixed minimum ventilation rate and the exhaust and return air dampers close and open, respectively.

During air-side economizer operation (**free cooling**), or any time air is exhausted to the outside at the air handler, the differential between supply and return airflow rates should be maintained. The difference should equal the pressurization flow plus flow through return and local exhausts. Most free-cooling systems have either a return or relief fan, which should be modulated to maintain the preset supply/return airflow differential.
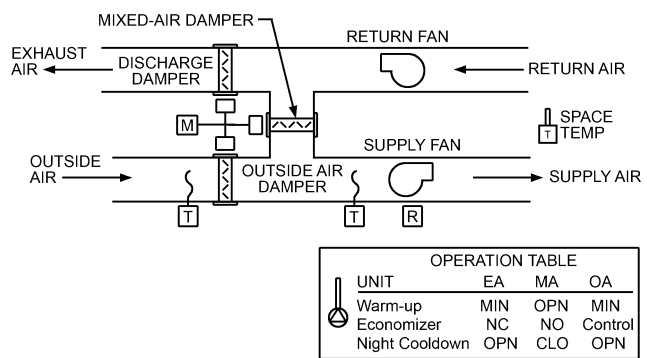
Fig. 24 Economizer Cycle Control

Modulating economizer systems achieve the mixed-air temperature set point by modulating outside air and recirculation dampers in sequence, as described in the section on Minimum Outside Air Control. When a single intake damper is used, the mixed-air temperature set point is maintained by resetting the outside airflow set point. When a minimum/maximum damper arrangement is used, the mixed-air temperature is achieved by directly controlling the dampers. Resetting the outside airflow set point results in more stable temperature control.

The relief air damper should be opened during free cooling, because it is expected that large quantities of supply air will need to leave the building along a planned path of flow and not an unplanned path, such as entry doors standing open. As an added level of security against negative airflow into the relief damper, a differential pressure sensor or bleed airflow sensor could be placed across the relief damper. This measured value would reset the return damper closed or increase the return fan speed to ensure outward flow of relief air.

In enthalpy economizer control, the economizer changeover temperature limit no longer assumes an outdoor humidity but rather also measures relative humidity to compare the calculated enthalpy difference between return and outside air. The economizer cycle is active only when outside conditions have a lower heat content than return air, to further reduce energy costs when latent loads are significant. The interlock function can be based instead on (1) a fixed enthalpy upper limit, (2) a comparison with return air so as not to exceed return air enthalpy, or (3) a combination of enthalpy and high-temperature limits. However, enthalpy-sensing devices require regular maintenance and calibration.

VAV warm-up control during unoccupied periods requires no outside air; typically, outside and exhaust dampers remain closed. The supply fan and return fan airflow are offset to maintain positive or negative duct pressurization.

Where outside conditions allow, night cooldown control (**night purge**) provides 100% outside air for cooling during unoccupied periods. The space is cooled to the space set point, typically 9°F above outside air temperature. Limit controls prevent operation if outside air is above space dry-bulb temperature, if outside dew-point temperature is excessive, or if outside dry-bulb temperature is too cold (typically 50°F or below). When outside air conditions are acceptable and the space requires cooling, the cooldown cycle is the first phase of the optimum start sequence.

Constant-Volume (CV) Systems

In a constant-volume system, supply and return fan airflow rates are manually set to meet the maximum airflow requirements for thermal load and ventilation. The air-handling unit's mixed-air dampers, cooling coil, and heating coil (where applicable) are controlled by supply air temperature. The supply air temperature set point is set to satisfy the zone with the maximum load, and, to improve energy efficiency, can be reset from the zone with the

greatest load. Reheat coils on constant-volume terminal boxes are controlled by individual space thermostats to establish the final space temperatures. If warm-up mode is used, the supply air set point is adjusted upward to the desired value.

The mixed-air dampers are sequenced with the cooling coil with or without overlap, depending on the design strategy. The mixed-air damper control can be enabled by a dry-bulb- or enthalpy-based economizer or a demand-controlled ventilation scheme (see the Variable-Air-Volume section for details). Balancing dampers may also be incorporated to ensure the required airflow for various positions of the mixed-air dampers.

During unoccupied periods when the fan must run for morning warm-up or night cooldown cycle, mixed-air dampers should be positioned to 100% return air to help achieve set point and to conserve energy. At the end of morning warm-up and the beginning of occupancy, when the space reaches set point, the unit switches to occupied mode. If the space reaches the warm-up set point before occupancy, the outside air damper should remain closed to minimize the additional heating energy needed. Morning warm-up occurs only once in a day. In the warm-up mode, with heating supplied by the air handling unit, terminal and perimeter heating units may be disabled as appropriate to use the lowest-cost energy source.

When the fan runs for night cooldown, the mixed-air dampers are positioned to 100% return air unless positioned by an economizer. In this case, the cooldown mode uses the economizer as the first stage of cooling and mechanical cooling as next stage(s) of cooling. When the space reaches the cooldown set point, the unit switches to occupied mode. If the space reaches the cooldown set point before occupancy, the system remains in occupied mode to prevent redundant cooldown operation. Night cooldown occurs only once in a day.

Changeover/Bypass Zoning Systems

Changeover/bypass zoning systems, often referred to as variable-volume/variable-temperature systems, are typically used to convert a single-zone constant-volume air-handling unit into multiple variable-volume temperature-controlled zones (Figure 25). The unit fan usually operates continuously in occupied mode, and cycles as required to maintain setback/setup zone temperatures in unoccupied mode. The unit remains a constant-volume unit and, as zones close off airflow to a particular zone, a static pressure sensor in the supply duct typically modulates a damper to bypass air back to the return duct to keep airflow across the unit's coils relatively constant. A controller on the unit turns on stages of heat or cooling based on zone thermostat requirements. Zone control is typically pressure-dependent, and the zone controllers modulate a damper between maximum and minimum position based on the zone's temperature
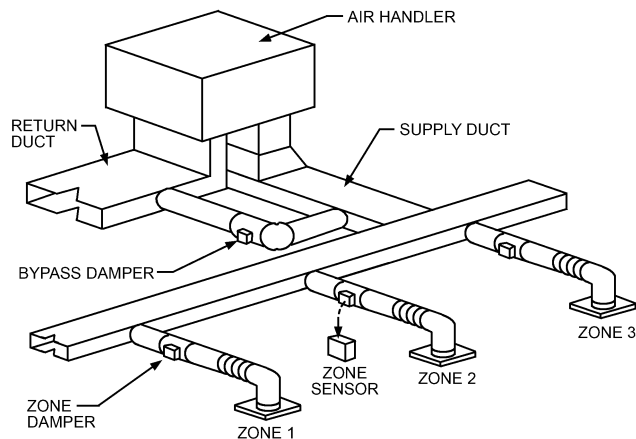
requirements and supply air temperature. Pressure-independent control is an option on some systems; the zone controller measures airflow to the zone and resets the air volume to the zone between maximum and minimum airflow limits, based on zone temperature requirements and supply air temperature. Digital controllers on the zone dampers "vote" for heating or cooling based on zone temperature and deviation from set point. When the vote favors heating, the unit controller stages heating on and broadcasts to the zone controllers that warm air is coming down the duct. Any zone requiring heat opens its damper, and any zone requiring cooling closes its damper to minimum position or flow. Similarly, when the vote is for cooling, the unit turns on stages of cooling and broadcasts to the zones that cool air is coming down the duct. If no zone requires heat or cooling, the supply fan remains on in occupied mode, but either keeps the heating and cooling off or cycles heating and cooling as required to maintain a supply temperature approximately equal to the zone temperature ±5°F.

These systems typically serve fewer than 15 zones per air-handling unit, and should serve zones with similar thermal loads (e.g., all internal zones or all zones on the same exterior exposure), so that the unit is not continually switching between heating and cooling.

Humidity Control

Humidity control relies on the output of a humidity sensor located either in the space or in the return air duct. Most comfort cooling involves some dehumidification. The amount of dehumidification is a function of the effective coil surface temperature and is limited by the coolant's freezing point. If water condensing out of the airstream freezes on the coil surface, airflow is restricted and, in severe cases, may be shut off. The practical limit is about 40°F dew point on the coil surface. As indicated in Figure 26, this results in a relative humidity of about 30% at a space temperature of 75°F, which is adequate for most commercial applications. When lower humidity is needed, a chemical dehumidifier is required.

Dehumidification can be achieved in several ways. One is to override control of the cooling coil. The temperature of the coil is lowered until sufficient moisture is removed from the supply air to maintain the humidity set point. When maximum relative humidity control is required, a space or return air humidistat is provided in addition to the space thermostat. To limit maximum humidity, a control function selects the higher of the output signals from the two devices and controls the cooling coil valve accordingly. A reheat coil may be required to maintain the space temperature if moisture removal results in too low a supply air temperature (Figure 27). If humidification is also provided, this cycle is sometimes called a

Fig. 25   Changeover/Bypass Zoning System
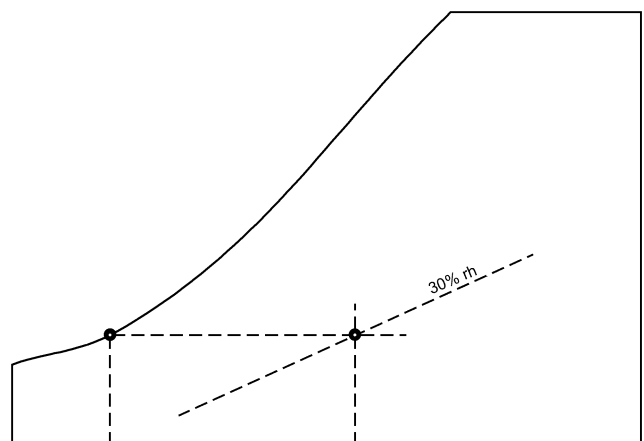
Fig. 26   Psychrometric Chart: Cooling and Dehumidifying, Practical Low Limit

constant-temperature, constant-humidity cycle. Although simple cooling by refrigeration maintains an upper limit to space humidity, without additional equipment it does not control humidity.

Sprayed-coil dehumidifiers (Figure 28) have been used for dehumidification. Space relative humidity ranging from 35 to 55% at 75°F can be obtained with this equipment; however, the costs of maintenance, reheat, and removal of solid deposits on the coil make the sprayed-coil dehumidifier less desirable than other methods.

A **desiccant-based dehumidifier** can lower space humidity below that possible with cooling/dehumidifying coils. This device adsorbs moisture using silica gel or a similar material. For continuous operation, heat is added to regenerate the material. The adsorption also generates heat (Figure 29). Figure 30 shows a typical control.

Humidification can be achieved by adding moisture to supply air, using evaporative pans (usually heated), steam jets, or atomizing spray tubes. A space or return air humidity sensor provides the necessary signal for the controller. A humidity sensor in the duct should be used to minimize moisture carryover or condensation in the duct (Figure 31). With proper use and control, humidifiers can achieve high space humidity, although they more often are used to maintain design minimum humidity during the heating season.

Terminal Units

A system is considered to be variable-volume if primary airflow to the space varies. Total airflow to the space (primary air + plenum air) may be constant for some terminal units, even in a variable-volume system.

Single-Duct Constant-Volume. Reheat terminals use a single constant-volume fan system that serves multiple zones (Figure 32). All delivered air is cooled to satisfy the greatest zone cooling load. Air delivered to other zones is then reheated with heating coils (hot-water, steam, or electric) in individual zone ducts. The reheat coil valve (or electric heating element) is reset as required to maintain the space condition. Because these systems consume more energy than VAV systems, they are generally limited to applications with fixed ventilation needs, such as hospitals and special processes or laboratories.

No fan control is required because the design, selection, and adjustment of fan components determine the air volume and duct static pressure. The same temperature air is supplied to all zones. However, the controller can allow the supply temperature to respond to demand from the greatest cooling load, thus conserving energy.

Single-Duct Variable-Volume. A **throttling VAV terminal** has an inlet damper that controls the flow of supply air (Figure 33). For spaces requiring heating, a reheat coil can be installed in the discharge. A common control sequence for this system (particularly with pneumatic controls) is the single maximum scheme depicted in

Fig. 29   Psychrometric Chart: Chemical Dehumidification

Fig. 27   Cooling and Dehumidifying with Reheat
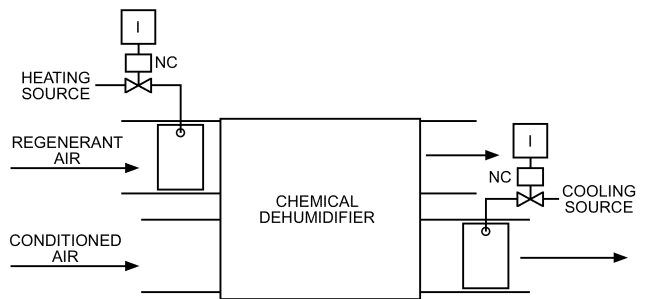
Fig. 30   Chemical Dehumidifier

Fig. 28   Sprayed-Coil Dehumidifier
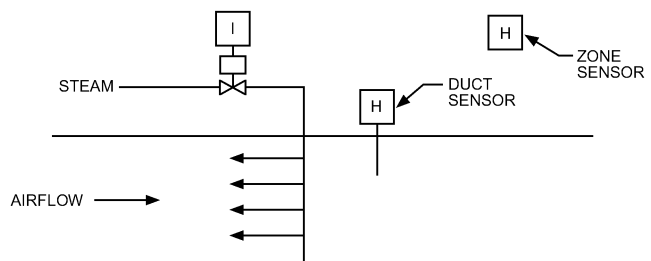
Fig. 31   Steam Jet Humidifier

Figure 33. In this sequence, as temperature in the space drops below the set point, the damper begins to close and reduce airflow to the space. When airflow reaches the minimum limit, the valve on the reheat coil begins to open.

One disadvantage of this sequence is that the minimum flow set point must be high enough to meet the design heating load at a supply air temperature that is low enough to prevent stratification (e.g., less than 90°F). Therefore, the minimum flow set point typically must be 30 to 50% of the maximum flow set point. This wastes a great deal of reheat and fan energy, particularly for zones that are very conservatively sized.

A much more energy-efficient sequence is the dual maximum sequence in Figure 34. As the space goes from design cooling load to design heating load, the airflow set point is first reset from the cooling maximum to the minimum. Then the supply air temperature is reset from minimum (e.g., 55°F) to maximum (e.g., 90°F), and the reheat coil is modulated to maintain the supply air temperature at set point. Lastly, the airflow set point is reset from the minimum up to the heating maximum. One of the advantages of the dual maximum sequence is that the minimum flow set point is not limited by stratification (as described for the single maximum) and can be set as low as 10 to 20% of the maximum flow, depending on ventilation requirements and the lowest nonzero controllable flow. Thus, the dual maximum sequence greatly reduces wasted reheat and fan energy, and should be used whenever DDC controls are used.
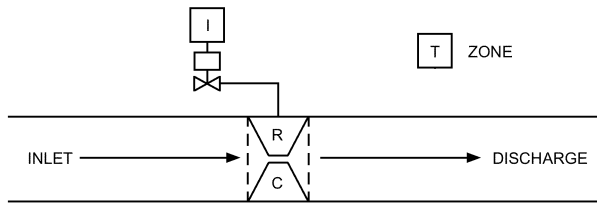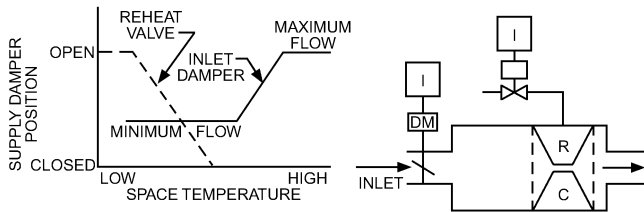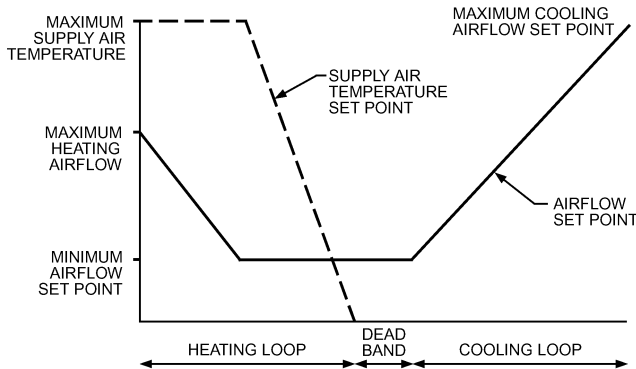
An **induction VAV terminal** controls space temperature by reducing supply airflow to the space and by inducing return air from the plenum into the airstream for the space (Figure 35). Both dampers are controlled simultaneously, so as the primary air opening decreases, the return air opening increases. When space temperature drops below the set point, the supply air damper begins to close and the return air damper begins to open.

A **bypass VAV terminal** has a damper that diverts part of the supply air into the return plenum (Figure 36). Control of the diverting damper is based on output of the space temperature sensor. When temperature in the space drops below the set point, the bypass damper begins to open, routing some supply air to the plenum, which reduces the amount of supply air entering the space. When the bypass is fully open, the reheat coil's control valve opens as required to maintain space temperature. A manual balancing damper in the bypass is adjusted to match the resistance in the discharge duct. In this way, the supply of air from the primary system remains at a constant volume. The maximum airflow through the bypass must be restricted to maintain minimum airflow into the space. Although airflow to the space is reduced, the fan's total airflow remains constant, so fan power and associated energy cost are not reduced. These terminals can be added to a single-zone constant-volume system to provide zoning without the energy penalty of a conventional reheat system. However, if a return or exhaust fan is not used and a majority of the terminals go to bypass, the return plenum may become positive in relation to the space, forcing return air back into the space.

A **series fan-powered VAV terminal unit** has an integral fan that supplies a constant volume of air to the space (Figure 37). In addition to enhancing air distribution in the space, a reheat coil can be added to maintain a minimum temperature in the space when the

Fig. 32   Single-Duct Constant-Volume Zone Reheat

Fig. 33   Throttling VAV Terminal Unit: Single Minimum Control Sequence

Fig. 34   Throttling VAV Terminal Unit: Dual Minimum Control Sequence
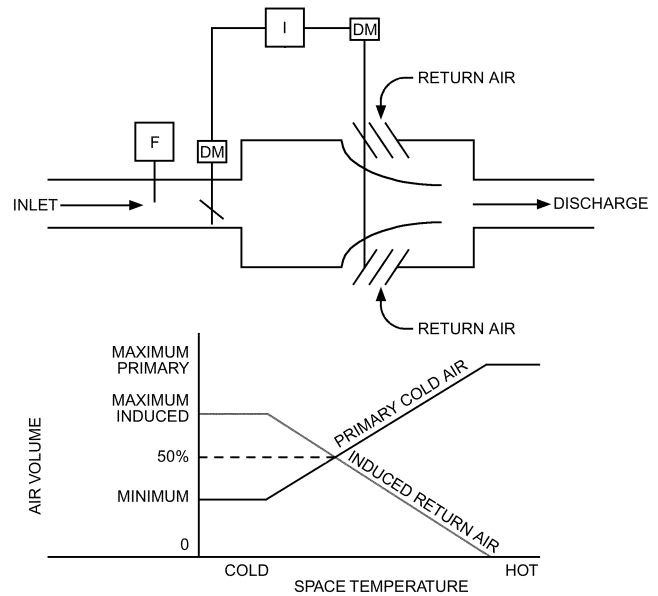
Fig. 35   Induction VAV Terminal Unit
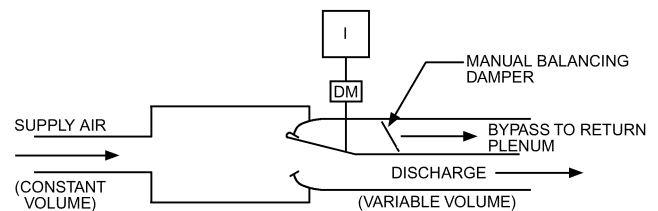
Fig. 36   Bypass VAV Terminal Unit

primary system is off. When the space is occupied, the fan runs constantly to provide a constant volume of air to the space. The fan can draw air from the return plenum to compensate for reduced supply air volume. As temperature in the space decreases below the set point, the supply air damper begins to close and the fan draws more air from the return plenum. Units serving the perimeter area of a building can include a reheat coil. Then, when supply air reaches its minimum volume, the valve to the reheat coil begins to open.

A **plenum** or **parallel fan terminal** has a fan that pulls air from the return plenum and mixes it with the supply air (Figure 38). A reheat coil may be placed in the discharge to the space or in the return plenum opening. The fan provides a minimum airflow to the space. Total airflow to the space is the sum of the fan output and supply air quantity. When space temperature drops below the set point, the supply air damper begins to reduce the quantity of supply air entering the terminal. Once the supply damper reaches its minimum position, the reheat coil valve starts to open. When the space is unoccupied and requires heating, the supply air damper is closed, the fan turns on, and the reheat coil valve modulates to maintain the unoccupied set point.

Dual-Duct Constant-Volume. A **mixing box terminal** generally is used where large amounts of ventilation at a low static
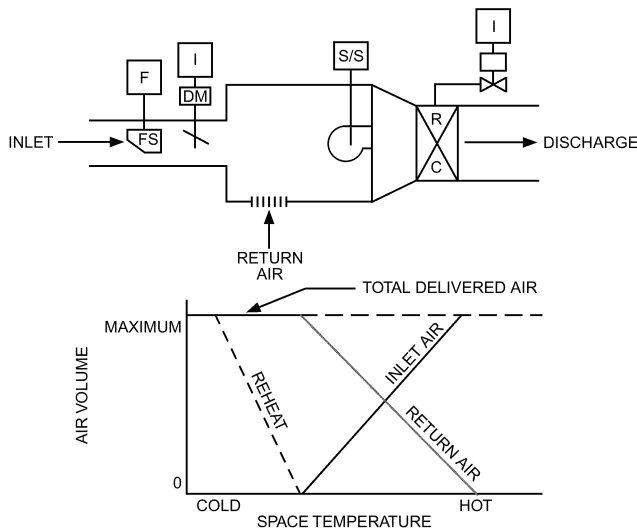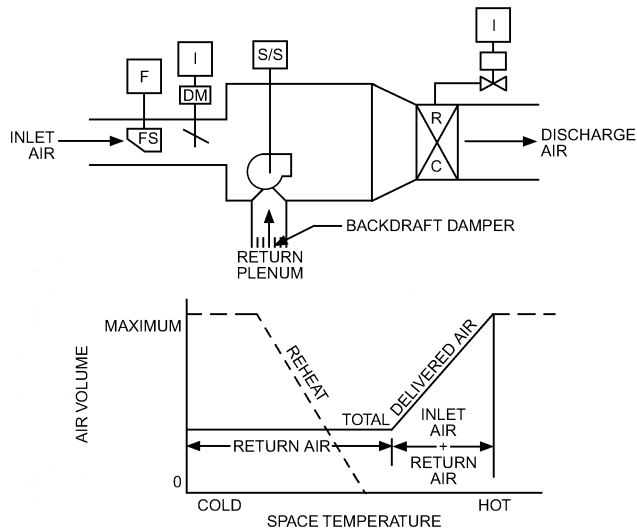
pressure are required. The hot- and cold-duct dampers are linked to operate in reverse directions. A space thermostat positions the mixing dampers through a damper actuator to mix warm and cool supply air. Discharge air volume depends on the static pressure in each supply duct at that location. Static pressures in the supply ducts vary because of the varying airflow in each duct (Figure 39).

Dual-duct constant-volume mixing box terminals are typically used in high-static-pressure applications where airflow quantity to each space is critical. The units are the same as those described in the previous paragraph, except that they include either an integral mechanical constant-volume regulator or an airflow constant-volume control furnished by the unit manufacturer (Figure 40).

Dual-Duct Variable-Volume. Mixing box terminals have inlet dampers on the heating and cooling supply ducts. These dampers are linked to operate in reverse directions, and require a single control actuator. Also, a sensor in the discharge monitors total airflow. The space thermostat controls inlet mixing dampers directly, and the airflow controller controls the volume damper. The space thermostat resets the airflow controller from maximum to minimum flow as the thermal load on the conditioned area changes. Figure 41 shows the control schematic and damper operation. Note that, in part of the control range, heating and cooling supply air mix.

Variable, constant-volume (zero-energy-band) dual-duct terminal units (Figure 42) have inlet dampers (with individual damper actuators and airflow controllers) on the cooling and heating supply ducts and no total airflow volume damper. The zero-energy-band (ZEB) space thermostat resets the airflow controller set points in sequence as the space load changes. The airflow controllers maintain adjustable minimum flows for ventilation (with no overlap of damper operations) in the ZEB when neither heating nor cooling is required.

Heat Pump. A heat pump is a refrigeration device that uses the evaporator to cool a warm space, as is typical of a window air conditioner, but uses heat that is normally rejected from the condenser

Fig. 37   Series Fan-Powered VAV Terminal Unit

Fig. 38   Plenum or Parallel Fan Terminal Unit
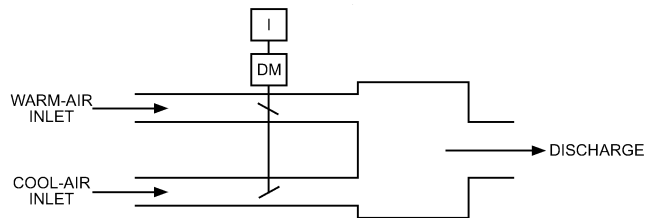
Fig. 39   Dual-Duct Mixing Box Terminal Unit
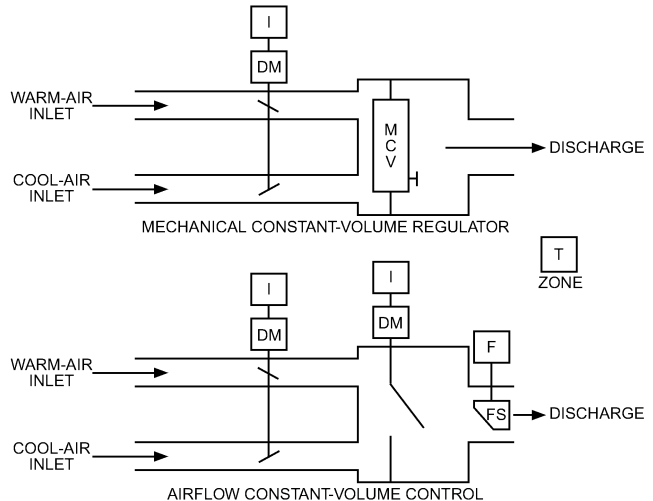
Fig. 40   Dual-Duct Pressure-Independent Constant-Volume Mixing Box Terminal Units

for heating. The air outside is cooled, and heat taken from the outside is "pumped" into the space. Many conventional means to control refrigeration equipment can be used to control heat pump heating and cooling cycles; see Chapters 8 and 45 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment* for details.

Air Handling

Generally, air is distributed by either single-duct or dual-duct systems. Airflow to each zone is controlled by a terminal box. A special case of a dual-duct system is a multizone unit with terminal boxes incorporated into the air handler. In this case, the hot and cold ducts are referred to as the **hot** and **cold decks**. One special multizone configuration has three decks, which may be used as an alternative (Figure 43). Zone dampers in this unit operate with sequenced dampers to either mix hot supply air with bypass air when the cold-deck damper is closed or mix cold supply air with bypass air when the hot-deck damper is closed.

A single-zone system (Figure 44) uses a constant-volume air handler (usually factory-packaged). No fan speed control is required, because fan volume and duct static pressure are set by design and component selection. Single-zone systems do not require terminal boxes, because zone temperature can be maintained by modulating the heating and cooling control valves in sequence.
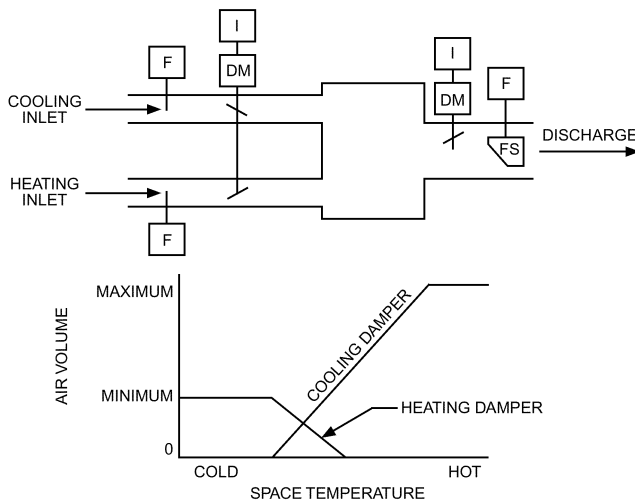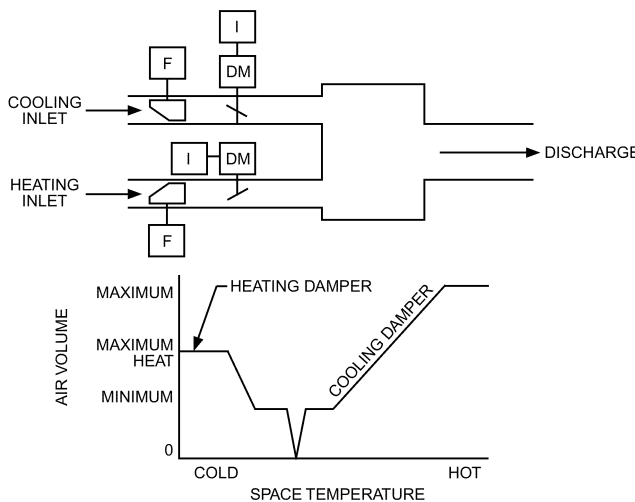
During warm-up, as determined by a time clock or manual switch, a constant heating supply air temperature is maintained. During warm-up and unoccupied cycles, outside air dampers should be closed.

A **unit ventilator** is designed to heat, ventilate, and cool a space by introducing up to 100% outside air. Optionally, it can cool and dehumidify with a cooling coil (either chilled-water or direct-expansion). Heating can be by hot water, steam, or electric resistance. Control of these coils can be by valves or by face-and-bypass dampers. Consequently, controls applied to unit ventilators are many and varied. The four most commonly used control schemes are Cycle I, Cycle II, Cycle III, and Cycle W.

Cycle I Control. Except during the warm-up stage, Cycle I (Figure 45) supplies 100% outside air at all times. During warm-up, the heating valve is open, the outside air (OA) damper is closed, and the return air (RA) damper is open. As temperature rises into the operating range of the space thermostat, the OA damper opens fully, and the RA damper closes. The heating valve is positioned to maintain space temperature. The airstream thermostat can override space thermostat action on the heating valve to prevent discharge air from dropping below a minimum temperature. Figure 45 shows positions of the heating valve and ventilation dampers in relation to space temperature.

Cycle II Control. During the heating stage, Cycle II (Figure 45) supplies a set minimum quantity of outside air. Outside air is gradually increased as required for cooling. During warm-up, the heating valve is open, the OA damper is closed, and the RA damper is open. As space temperature rises into the operating range of the space thermostat, ventilation dampers move to their set minimum ventilation positions. The heating valve and ventilation dampers are operated in sequence as required to maintain space temperature. The airstream thermostat can override space thermostat action on the heating valve and ventilation dampers to prevent discharge air from dropping below a minimum temperature. Figure 45 shows the relative positions of the heating valve and ventilation dampers with respect to space temperature.

Fig. 41   Pressure-Independent Dual-Duct VAV Terminal Unit

Fig. 42   Variable, Constant-Volume (ZEB) Dual-Duct Terminal Unit
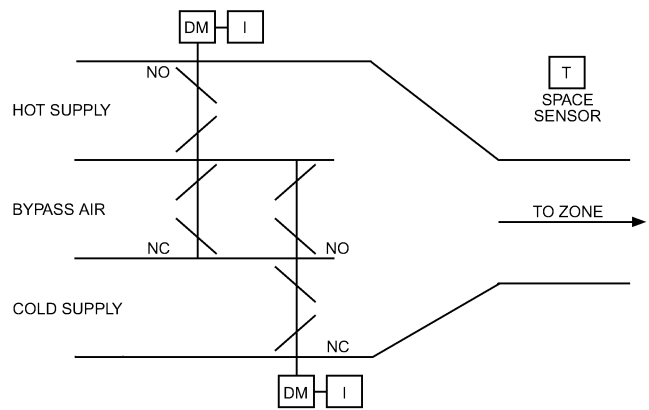
Fig. 43   Zone Mixing Dampers: Three-Deck Multizone System
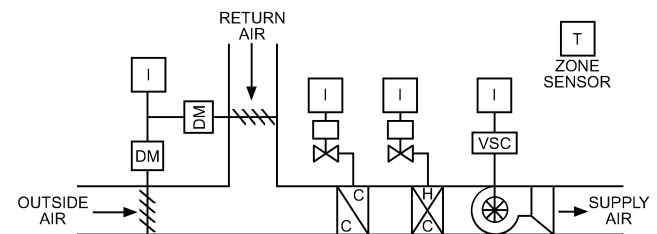
Fig. 44   Single-Zone Fan System

Cycle III Control. During heating, ventilating, and cooling stages, Cycle III (Figure 46) supplies a variable amount of outside air as required to maintain the air entering the heating coil at a fixed temperature (typically 55°F). When heat is not required, this air is used for cooling. During warm-up, the heating valve is open, the OA air damper is closed, and the RA damper is open. As the space temperature rises into the operating range of the space thermostat, ventilation dampers control the air entering the heating coil at the set temperature. Space temperature is controlled by positioning the heating valve as required. Figure 46 shows the relative positions of the heating valve and ventilation dampers with respect to space temperature.

Day/night thermostats are frequently used with any of these control schemes to maintain a lower space temperature during unoccupied periods by cycling the fan with the outside air damper closed. Another common option is a low-temperature limit control placed next to the heating coil, to turn off the unit when near-freezing temperatures are sensed.

Cycle W Control. Cycle W is similar to Cycle II, except that the heating valve is controlled by the room thermostat and the dampers are controlled by the low-limit thermostat (Figures 45 and 47).

Makeup air units (Figure 48) replace air exhausted from the building through exfiltration or by laboratory or industrial processes. Makeup air must be at or near space conditions to minimize uncomfortable air currents. The makeup air fan is usually turned on, either manually or automatically, whenever exhaust fans are turned on. However, the fan should not start until the outside air damper is fully open as proven by an end switch. The two-position outside air damper remains closed when the makeup fan is not in operation. The outside air limit control opens the preheat coil valve when outside air temperature drops to the point where the air requires heating to raise it to the desired supply air temperature. A capillary element thermostat located adjacent to the coil shuts the fan down for low-temperature detection if air temperature approaches freezing at any spot along the sensing element.

Fig. 45 Cycles I, II, and W Control Arrangements
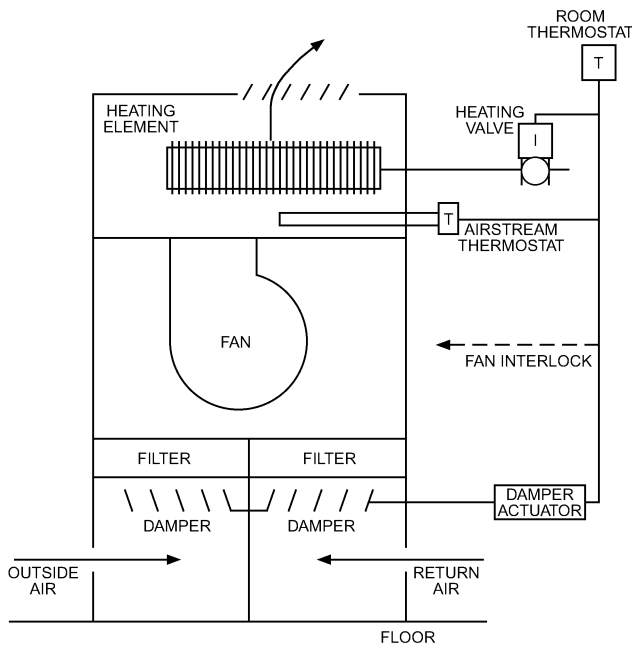
Fig. 46 Cycle III Control Arrangement
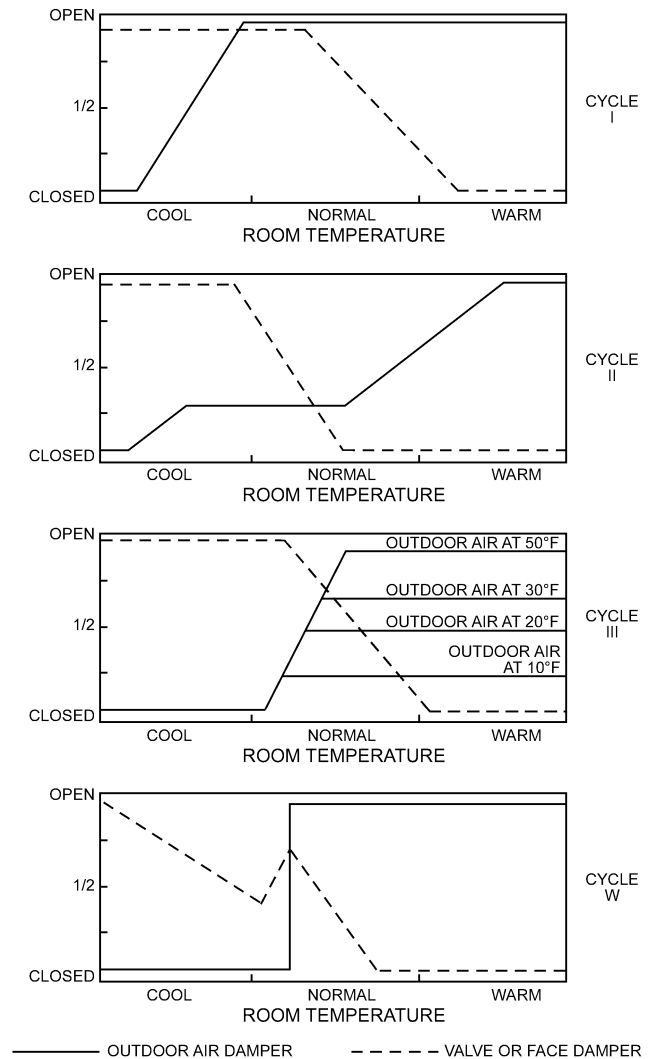
Fig. 47 Valve and Damper Positions with Respect to Room Temperature

Multizone, Single-Duct System

This system (Figure 49) is most effective where all zones are in either heating or cooling mode at the same time. When necessary and where energy regulations allow it, reheat can be used to accommodate systems with simultaneous heating and cooling loads.

Multizone, Dual-Duct Systems

A **single supply fan system** uses a single fan to supply separate heating and cooling ducts (Figure 50). Terminal mixing boxes are used to control the zone temperature. Static control is similar to that in VAV single-duct systems, except that static pressure sensors are needed in each supply duct. A controller allows the sensor detecting the lowest pressure to control the fan output, thus ensuring that there is adequate static pressure to supply the necessary air for all zones.

Control of a return air fan is similar to that described in the section on Fans, in the paragraph on Return Fan Static Control. Flow stations are usually located in each supply duct, and a signal corresponding to the sum of the two airflows is transmitted to the RA fan volume controller to establish the set point of the return fan controller.

The hot deck has its own heating coil, and the cold deck has its own cooling coil. Each coil is controlled by its own **discharge air temperature controller**. The controller set point may be reset from the greatest representative demand zone: based on zone temperature, the hot deck may be reset from the zone with the greatest heating demand, and the cold deck from the zone with the greatest cooling demand.

Control based on the zone requiring the most heating or cooling increases operation economy because it reduces the energy delivered at less-than-maximum load conditions. However, the expected economy is lost if air quantity to a zone is too low, a zone's temperature set point is set to an extreme value, a zone sensor is placed so that it senses spot loads (from coffeepots, the sun, copiers, etc.), a sensor is located in an unoccupied zone, or a zone sensor malfunctions. In these cases, a weighted average of zone signals can recover the benefit at the expense of some comfort in specific zones.

Ventilation dampers (outside, return, and exhaust air) are controlled for cooling, with outside air as the first stage of cooling in sequence with the cooling coil from the cold-deck discharge temperature controller. Control is similar to that in single-duct systems.
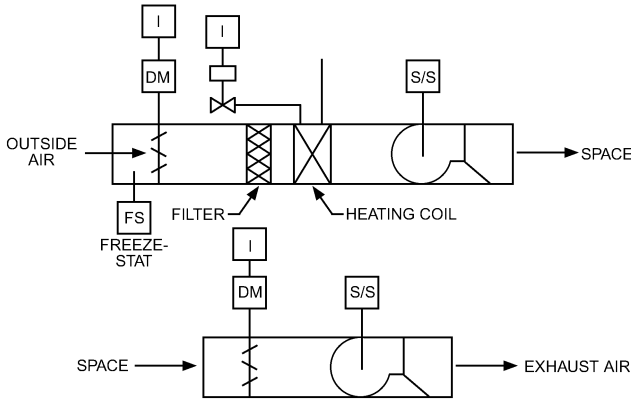
Fig. 48   Makeup Air Unit
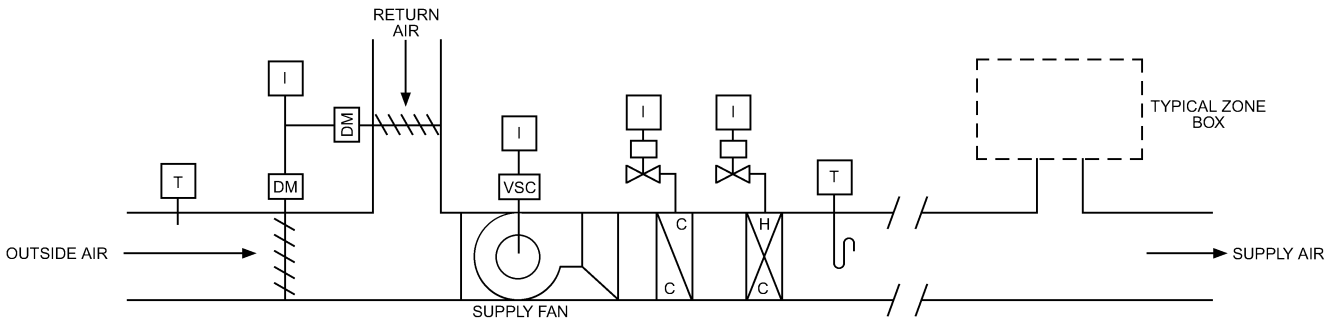
Fig. 49   Multizone Single-Duct System
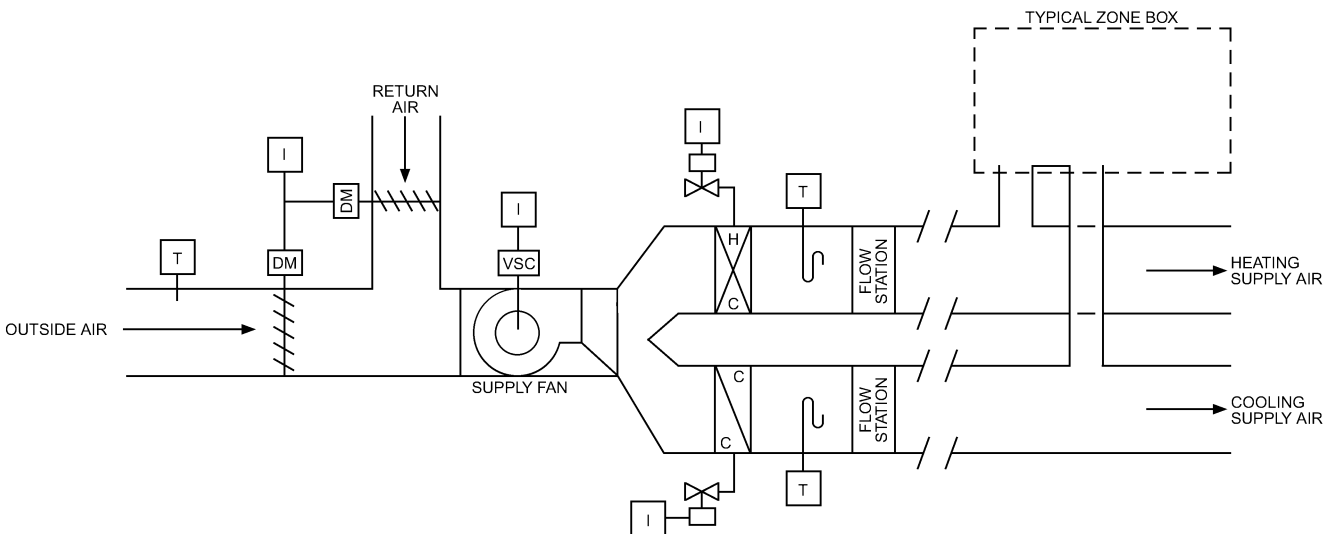
Fig. 50   Dual-Duct Single-Supply Fan System
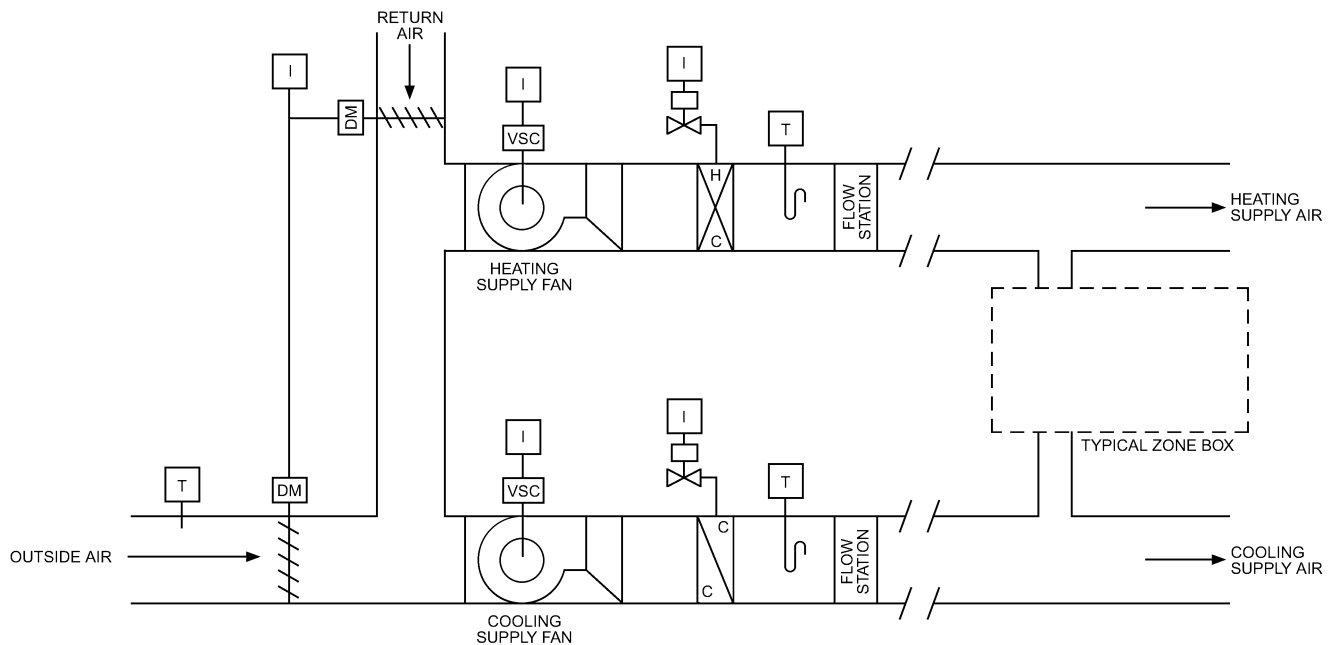
Fig. 51   Dual-Supply Fan System

A more accurate OA flow-measuring system can replace the minimum positioning switch.

Dual-supply fan systems (Figure 51) use separate supply fans for the heating and cooling ducts. Static-pressure control is similar to that for VAV dual-duct single-supply fan systems, except that each supply fan has its own static pressure sensor and control. If the system has a return air fan, volume control is similar to that described in the section on Fans, in the paragraph on Return Fan Static Control. Temperature, ventilation, and humidity control are similar to those for VAV dual-duct single-supply fan systems.

WATER HEATING

A basic constant-volume hydronic system is shown in Figure 52. In a primary-secondary system, a variable-speed drive could be added to the secondary pump motor and the three-way valves could be changed to two-way valves to save energy.

SPECIAL APPLICATIONS

Mobile Unit Control

The operating point of any control that relies on pressure to operate a switch or valve varies with atmospheric pressure. Normal variations in atmospheric pressure do not noticeably change the operating point, but a change in altitude affects the control point to an extent governed by the change in absolute pressure. This pressure change is especially important with controls selected for use in land and aerospace vehicles that are subject to wide variations in altitude. The effect can be substantial; for example, barometric pressure decreases by nearly one-third as altitude increases from sea level to 10,000 ft.

In mobile applications, three detrimental factors are always present in varying degrees: vibration, shock, and acceleration forces. Controls selected for service in mobile units must qualify for the specific conditions expected in the installation. In general, devices containing mercury switches, slow-moving or low-force contacts, or mechanically balanced components are unsuitable for mobile applications; electronic solid-state devices are generally less susceptible to these three factors.
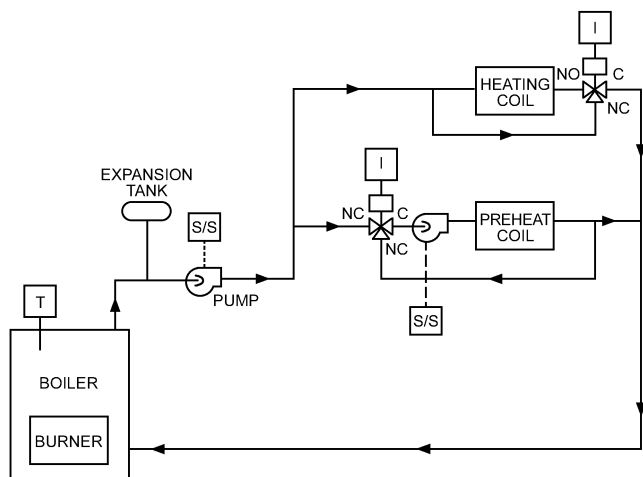
Fig. 52   Load and Zone Control in Constant-Volume System

Explosive Atmospheres

Sealed-in-glass contacts are not considered explosionproof; therefore, other means must be provided to eliminate the possibility of a spark in an explosive atmosphere.

When using electric control, the control case and contacts can be surrounded with an explosionproof case, allowing only the capsule and the capillary tubing to extend into the conditioned space. It is often possible to use a long capillary tube and mount the instrument case in a nonexplosive atmosphere. This method can be duplicated with an electronic control by placing an electronic sensor in the conditioned space and feeding its signal to an electronic transducer located in the nonexplosive atmosphere.

Because a pneumatic control uses compressed air, it is safe in otherwise hazardous locations. However, many pneumatic controls interface with electrical components. All electrical components require appropriate explosionproof protection.

Sections 500 to 503 of the *National Electrical Code* (NFPA *Standard* 70) include detailed information on electrical installation protection requirements for various types of hazardous atmospheres.
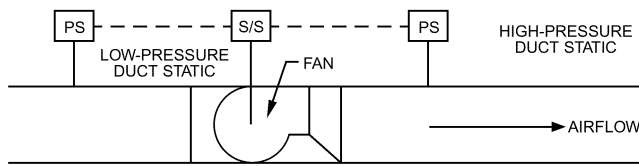
Fig. 53   High-Limit Static Pressure Controller

Duct Static Pressure Limit Control

In addition to the remote static-pressure controllers, a high- and low-limit static pressure controller should be placed at the fan discharge and inlet (Figure 53) to turn the fan off or limit discharge static pressure in the event of excessive duct pressure (e.g., when a fire or smoke damper closes between the fan and the remote sensor). Supply fan static pressure control devices such as inlet guide vanes and variable-speed drives should be interlocked to move to the minimum-flow or closed position when the fan is not running; this precaution prevents fan overload or damage to ductwork on start-up.

When selecting automatic controls, the type needed to control high or low limits (safety) must be considered. This control may be inoperative for days, months, or years, but then must operate immediately to prevent serious damage to equipment or property. Separate operating and limit controls are always recommended, even for the same functions.

Duct static limit control prevents excessive duct pressures, usually at the discharge of the supply fan. Two variations are used: (1) the fan shutdown type, which is a safety high-limit control switch that turns fans off; and (2) the controlling high-limit speed control duct pressure reset type (Figure 53), which is used in systems that have zone fire dampers. When the zone fire damper closes, and the duct static pressure sensor is downstream of the zone, duct pressure falls from lack of air, causing the duct static control to increase fan speed; however, the controlling high limit overrides and stop the fan.

DESIGN CONSIDERATIONS AND PRINCIPLES

In designing and selecting the HVAC system for the entire building, the type, size, use, and operation of the structure must be considered. Subsystems such as fan and water supply are normally controlled by local automatic control or a local loop control, which includes the sensors, controllers, and controlled devices used with a single HVAC system and excludes any supervisory or remote functions such as reset and start/stop. However, local control is frequently extended to a central control point to diagnose malfunctions that might result in damage from delay, and to reduce labor and energy costs. Special modes of operation may be required to allow for load shedding, purge, warm-up, cooldown, and lockdown. Initiators may be manual or automatic, based on weather, announcements of extraordinary events, high concentrations of expected and therefore measured hazardous gases, or daily schedules reset by outside air temperature.

Distributed processing using microprocessors has augmented computer use at many locations other than the central control point. The local loop controller can be a DDC instead of a pneumatic or electric thermostat, and some energy management functions may be performed by a DDC.

Because HVAC systems are designed to meet maximum design conditions, they nearly always function at partial capacity. The system must be adjusted and operated for many years, so the simplest control that produces the necessary results is usually the best.

Extraordinary Incidents

Building owners and design engineers are sometimes interested in applying the building automation system (BAS) to implement strategies that protect occupants from airborne attack. It is crucial that the engineer does not approach this complex topic as a control system issue. The BAS may include protective features, but only in the context of a comprehensively designed ventilation system. A protective ventilation strategy only makes sense in the context of a thorough risk assessment and an overall security plan. If a protective ventilation strategy is attempted, it is crucial to consider every air movement device and pathway, not just the main fan(s) and damper(s). It is also necessary to consider possible interaction of a protective operation with other emergency control operations, such as the response to a fire/life safety device (e.g., a smoke detector).

Many references are available to guide an engineer or building owner in organizing a comprehensive plan, including ASHRAE (2003b), FEMA (2003), and NIOSH (2002). Also see Chapter 58 for more information on this topic.

Mechanical and Electrical Coordination

Even a pneumatic control system includes wiring, conduit, switchgear, and electrical distribution for many electrical devices. The mechanical designer must inform the electrical designer of the total electrical requirements if controls are to be wired by the electrical contractor. Requirements include (1) the devices to be furnished and/or connected, (2) electrical load, (3) location of electrical items, and (4) a description of each control function.

Coordination is essential. Proper coordination should produce a control diagram that shows the interface with other control elements to form a complete and usable system. As an option, the control engineer may develop a complete performance specification and require the control contractor to install all wiring related to the specified sequence. The control designer must run the final checks of drawings and specifications. Both mechanical and electrical specifications must be checked for compatibility and uniformity.

Building and System Subdivision

The following factors must be considered in the building and mechanical system subdivision:

- Varying heating and cooling loads: ability to heat or cool any area of a building at any time
- Occupancy schedules and flexibility to meet needs without undue initial and/or operating costs
- Fire and smoke control and possibly compartmentation that matches the air-handling layout and operation

Energy-Efficient Controls

The U.S. Green Building Council's (USGBC) Leadership in Energy Efficient Design (LEED) program for new construction and existing buildings provides guidance on designing and building commercial, institutional, and government buildings to produce quantifiable benefits for occupants, owners, and the environment.

During design and construction, LEED provides many opportunities for using a building automation system (BAS). LEED awards points, based on design criteria, to determine at which level a building is certified: platinum, gold, silver, or certified. (For specifics, see http://www.usgbc.org.) Many of these points depend on the sophistication, flexibility, and power of the BAS (which can provide up to 40% of the required points for a certification level), not only for comfort and energy efficiency, but also for sustainability verification for the facility's lifetime.

Although many publications address green and LEED design for buildings and equipment selection, **green controls** is a relatively new term and is still evolving. For the most up-to-date information, consult the latest publications in the field.

Applications. It is recommended that the LEED design team choose the controls consultant/contractor and to have them on board with the team early in design, allowing for controls input on the control schemes.

For any facility, the BAS provides thermal comfort and routine programming (e.g., occupied/unoccupied). Under LEED, the controls consultant or contractor uses the BAS for benchmarking and alarming when reference points are exceeded (e.g., monitoring facility electrical use). Once a baseline is established, programs with established alarm limits can alert the owner if the facility exceeds the baseline by 10% or more, so corrections can be made and continued higher utility expenses avoided. Depending on the facility, this may be monitored for hourly, daily, weekly, or monthly comparison.

The BAS can also

- Turn solar panels for optimum sun exposure
- Adjust blinds and awnings
- Keep indoor air quality (IAQ) acceptable by adjusting outside air (OA) without overventilating
- Monitor and adjust indoor and outdoor lighting
- Control irrigation based on weather
- Collect weather data
- Track scheduling hours for occupancy
- Monitor equipment run times and set points
- Track electricity use profiles
- Monitor efficiency of large equipment performance [e.g., chillers, variable-frequency-drive (VFD) pumping, boilers]

All of these factors affect building sustainability.

Because the BAS operates in real time, and can compare real-time data to previously defined baselines, it is a valuable tool. Open protocols allow the BAS to monitor, control, and provide critical alarming for non-HVAC equipment (e.g., for power monitoring, chiller performance, VFDs for VAV systems or variable-speed pumping, water efficiency, emergency generators, indoor and outdoor lighting, boilers) for a minimal investment.

The BAS provides an excellent tool for commissioning both HVAC and other equipment, as required by LEED. Its data acquisition abilities allow comparisons of daily performance as building use changes, thereby allowing the commissioning agent to determine whether equipment is operating properly, and allowing the owner to compare real-time data to previously defined benchmarks in **measurement and verification (M&V)**. Typical operation sequences, such as optimizing outside air, chiller efficiency, and multiple sensing points for providing thermal comfort, are, however, still used, and are critical for maintaining sustainability.

Perhaps the most important aspect of green controls is training the owner. Many owners do not fully realize the capabilities of BAS, many of which are intangible and somewhat obscure, so it is critical that the owner be given proper training in using the controls system. The order in which training takes place is equally important: mechanical equipment training should come first, then operation and maintenance (O&M) and controls layout configurations, use of the controls system to provide thermal comfort and maintain equipment, and, finally, written M&V procedures to maintain sustainability.

If the facility cannot justify a full-time energy manager, then the owner should consider third-party contracting to ensure the facility maintains its design energy efficiency.

CONTROL PRINCIPLES FOR ENERGY CONSERVATION

Temperature and Ventilation Control. VAV systems are typically designed to supply constant-temperature air at all times. To conserve central plant energy, the temperature of supply air can be raised in response to demand from the zone with the greatest load (load analyzer control). However, because more cool air must then be supplied to match a given load, the mechanical cooling energy saved may be offset by an increase in fan energy. Equipment operating efficiency should be studied closely before implementing temperature reset in cooling-only VAV systems.

Outside, return, and exhaust air ventilation dampers are controlled by the discharge air temperature controller to provide free cooling as the first stage in the cooling sequence. When outside air temperature rises to the point that it can no longer be used for cooling, an outside air limit (economizer) control overrides the discharge controller and moves ventilation dampers to the minimum ventilation position. An enthalpy control system can replace outside air limit control in some climates.

After the general needs of a building have been established and the building and system subdivision has been made, the mechanical system and its control approach can be considered. Designing systems that conserve energy requires knowledge of (1) the building, (2) its operating schedule, (3) the systems to be installed, and (4) ASHRAE *Standard* 90.1. The principles or approaches that conserve energy are as follows:

- *Run equipment only when needed*. Schedule HVAC unit operation for occupied periods. Run heat at night only to maintain internal temperature between 55 and 60°F to prevent freezing. Start morning warm-up as late as possible to achieve design internal temperature by occupancy time, considering residual space temperature, outside temperature, and equipment capacity (optimum start control). Under most conditions, equipment can be shut down some time before the end of occupancy, depending on internal and external load and space temperature (optimum stop control). Calculate shutdown time so that space temperature does not drift out of the selected comfort zone before occupancy ends.
- *Sequence heating and cooling*. Do not supply heating and cooling simultaneously unless it is requested for humidity control. Central fan systems should use cool outside air in sequence between heating and cooling. Zoning and system selection should eliminate, or at least minimize, simultaneous heating and cooling. Also, humidification and dehumidification should not take place concurrently.
- *Provide only the heating or cooling actually needed*. Reset the supply temperature of hot and cold air (or water).
- *Supply heating and cooling from the most efficient source*. Use free or low-cost energy sources first, then higher-cost sources as necessary.
- *Apply outside air control*. When on minimum outside air, use no less than that recommended by ASHRAE *Standard* 62.1. In areas where it is cost-effective, use enthalpy rather than dry-bulb temperature to determine whether outside or return air is the most energy-efficient air source for the cooling mode.

System Selection

The mechanical system significantly affects the control of zones and subsystems. System type and number and location of zones influence the amount of simultaneous heating and cooling that occurs. For perimeter areas, heating and cooling should be controlled in sequence to minimize simultaneous heating and cooling. In general, this sequencing must be accomplished by the control system because only a few mechanical systems (e.g., two-pipe and single-coil) have the ability to prevent simultaneous heating and cooling. Systems that require engineered control systems to minimize simultaneous heating and cooling include the following:

- *VAV cooling with zone reheat*. Reduce cooling energy and/or air volume to a minimum before applying reheat.
- *Four-pipe heating and cooling for unitary equipment*. Sequence heating and cooling.
- *Dual-duct systems*. Condition only one duct (either hot or cold) at a time. The other duct should supply a mixture of outside and return air.
- *Single-zone heating/cooling*. Sequence heating and cooling.

Some exceptions exist, such as dehumidification with reheat.

Control zones are determined by the location of the thermostat or temperature sensor that sets the requirements for heating and cooling supplied to the space. Typically, control zones are for a room or an open area of a floor.

Many U.S. jurisdictions no longer permit constant-volume systems that reheat cold air or that mix heated and cooled air. Such systems should be avoided. If selected, they should be designed for minimal use of reheat through zoning to match actual dynamic loads and resetting cold and warm air temperatures based on the zone(s) with the greatest demand. Heating and cooling supply zones should be structured to cover areas of similar load. Areas with different exterior exposures should have different supply zones.

Systems that provide changeover switching between heating and cooling prevent simultaneous heating and cooling. Some examples are hot or cold secondary water for fan-coils or single-zone fan systems. They usually require small operational zones, which have low load diversity, to allow changeover from warm to cold water without occupant dissatisfaction.

Systems for building interiors usually require year-round cooling and are somewhat simpler to control than exterior systems. These interior areas normally use all-air systems with a constant supply air temperature, with or without VAV control. Proper control techniques and operational understanding can reduce the energy used to treat these areas. Avoid reheat. General load characteristics of different parts of a building may lead to selecting different systems for each.

Load Matching

With individual room control, the environment in a space can be controlled more accurately and energy can be conserved if the entire system can be controlled in response to the major factor influencing the load. Thus, water temperature in a water-heating system, steam temperature or pressure in a steam-heating system, or delivered air temperature in a central fan system can be varied as building load varies. Control of the entire system relieves individual space controls of part of their burden and provides more accurate space control. Also, modifying the basic rate of heating or cooling input in accordance with the entire system load reduces losses in the distribution system.

The system must always satisfy the area with the greatest demand. Individual controls handle demand variations in the area the system serves. The more accurate the system zoning, the greater the control, the smaller the distribution losses, and the more effectively space conditions are maintained by individual controls.

Buildings or zones with a modular arrangement can be designed for subdivision to meet occupant needs. Before subdivision, operating inefficiencies can occur if a zone has more than one thermostat. In an area where one thermostat activates heating while another activates cooling, the terminals should be controlled from a single thermostat until the area is properly subdivided.

Size of Controlled Area

No individually controlled area should exceed about 5000 ft^2 because the difficulty of obtaining good distribution and of finding a representative location for space control increases with zone area. Each individually controlled area must have similar load characteristics throughout. Equitable distribution, provided through competent engineering design, careful equipment sizing, and proper system balancing, is necessary to maintain uniform conditions throughout an area. The control can measure conditions only at its location; it cannot compensate for nonuniform conditions caused by improper distribution or inadequate design. Areas or rooms having dissimilar load characteristics or different conditions to be maintained should be controlled individually. The smaller the controlled area, the better the control and the performance and flexibility.

Location of Space Sensors

Space sensors and controllers must be located where they accurately sense the variables they control and where the condition is representative of the area (zone) they serve. In large open areas having more than one zone, thermostats should be located in the middle of their zones to prevent them from sensing conditions in surrounding zones. Typically, space temperature controllers or sensors are placed in the following locations.

- **Wall-mounted thermostats** or **sensors** are usually placed on inside walls or columns in the space they serve. Avoid outside wall locations. Mount thermostats at generally accessible heights according to the Americans with Disabilities Act (ADA) (USDOJ 1994) (usually 48 in.) and in locations where they will not be affected by heat from sources such as direct sun rays, wall pipes or ducts, convectors, or direct air currents from diffusers or equipment (e.g., copy machines, coffeemakers, refrigerators). The wall itself should be sealed tightly if it penetrates a pressurized supply air plenum either under the floor or overhead. Air circulation should be ample and unimpeded by furniture or other obstructions, and the thermostat should be protected against mechanical injury. Thermostats in spaces such as corridors, lobbies, or foyers should be used to control those areas only.
- **Return air thermostats** can control floor-mounted unitary conditioners such as induction or fan-coil units and unit ventilators. On induction and fan-coil units, the sensing element is behind the return air grille. On classroom unit ventilators that use up to 100% outside air for natural cooling, however, a forced-flow sampling chamber should be provided for the sensing element, which should be located carefully to avoid radiant effect and to ensure adequate air velocity across the element.

  If return air sensing is used with a central fan system, locate the sensing element as near as possible to the space being controlled to eliminate any influence from other spaces and the effect of any heat gain or loss in the duct. Where supply/return light fixtures are used to return air to a ceiling plenum, the return air sensing element can be located in the return air opening. Be sure to offset the set point to compensate for heat from the light fixtures.
- **Diffuser-mounted thermostats** usually have sensing elements mounted on circular or square ceiling supply diffusers and depend on aspiration of room air into the supply airstream. They should be used only on high-aspiration diffusers adjusted for a horizontal air pattern. The diffuser on which the element is mounted should be in the center of the occupied area of the controlled zone.
- **CO$_2$ sensors** are usually located in spaces with high occupant densities (e.g., conference rooms, auditoriums, courtrooms). Locating the sensor in return air ducts/plenums that serve multiple spaces measures average concentrations and does not provide information on CO$_2$ levels in rooms with the highest concentrations.

Commissioning

Commissioning is the process of ensuring that systems are designed, installed, functionally tested, and capable of being operated and maintained in conformity with the design intent. Commissioning HVAC systems begins with planning and includes design, construction, start-up, acceptance, and training, and can be applied throughout the life of the building.

For HVAC systems, **functional performance testing (FPT)** is an important part of the commissioning process. FPT is the process of determining the ability of HVAC system to deliver heating, ventilating, and air conditioning in accordance with the final design intent. Commissioning is team-oriented and generally involves cooperation of various parties, including the owner, design engineers, and contractors and subcontractors. A commissioning authority (the designated person, company, or agent who implements the overall commissioning process) generally leads the process. Each commissioning process must have a plan that defines the commissioning

process and is developed in increasing detail as the project progresses. Phases include plan, design, construction, and acceptance. The most useful tool used to challenge (simulate changes to) systems operation is the control system itself. A DDC system provides the added convenience of central execution of test steps, and the ability to record responses. Commissioning the DDC system must occur before it can be used to validate the HVAC systems. Commissioning DDC systems is discussed in ASHRAE GPC 11. Commissioning HVAC systems is recommended for construction of new buildings, and should be repeated periodically in existing buildings. See Chapter 42 and ASHRAE *Guidelines* 0 and 1 for more information.

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CHAPTER 47

SOUND AND VIBRATION CONTROL

H VAC equipment is one of the major sources of noise in a building, and its effect on the interior acoustical environment is important. Further, noise from outside equipment often propagates to the community. Therefore, mechanical equipment must be selected, and equipment spaces designed, with an emphasis on both the intended uses of the equipment and the goal of providing acceptable sound levels in occupied spaces of the building in which the equipment is located and in the community. Furthermore, operation of HVAC equipment causes vibrations that can propagate into occupied spaces. Vibration can create uncomfortable conditions for occupants, and often creates secondary noise sources (e.g., vibrating walls, floors, piping).

In this chapter, *sound* and *noise* are used interchangeably, although only *unwanted* sound is considered to be noise.

The system concept of noise control is used throughout this chapter: each of the components is thought of as being related to the source-path-receiver chain. The noise-generating mechanism is the source of the sound, which travels from the source via a path, which can be through the air (airborne) or through the structure (structureborne) until it reaches the ear of the listener.

Noise propagates from the sources through the air distribution duct systems, through the structure, and through combinations of paths, reaching the occupants. Components of the mechanical system (e.g., fans, dampers, diffusers, junctions) all may produce sound by the nature of the airflow through and around them. As a result, almost all components must be considered. Because sound travels effectively in the same or opposite direction of airflow, downstream and upstream paths are often equally important.

This chapter provides basic sound and vibration principles and data needed by HVAC system designers. It is divided into two main sections: one on sound, the other on vibration. Many of the equations associated with sound and vibration control for HVAC may be found in Chapter 7 of the 2005 *ASHRAE Handbook—Fundamentals* and in Chapter 42 of the 1991 *ASHRAE Handbook—HVAC Applications*. Additional technical discussions along with detailed HVAC component and system design examples can be found in the references. Specifically, guidelines for the acoustical design and related construction phases associated with HVAC systems, for troubleshooting sound and vibration problems in HVAC systems, and for HVAC sound and vibration specifications are contained in Schaffer (1991).

The preparation of this chapter is assigned to TC 2.6, Sound and Vibration Control.

DATA RELIABILITY

Data in this chapter come both from consulting experience and research studies. Use caution when applying the data, especially for situations that extrapolate from the framework of the original research. Although specific uncertainties cannot be stated for each data set, the sound levels or attenuation data are probably within 2 dB of measured or expected results. However, significantly greater variations may occur, especially in low frequency ranges and particularly in the 63 Hz octave band. Specific data sets may have a wide uncertainty range, but experience suggests that, if done correctly, system estimates that combine data sets usually compare within about 5 dB of measured levels.

SOUND GENERATION AND CONTROL

ACOUSTICAL DESIGN OF HVAC SYSTEMS

Noise control in HVAC system design involves examining sound and vibration sources, transmission paths, and receivers. Sources are the components that either generate noise and vibration (e.g., fans or pumps) or produce noise when airflow passes through them (e.g., dampers or diffusers). Paths are the routes by which the sound travels: through the air, over barriers, or along a ducted system. Receivers are usually the people who occupy a building or live in the nearby community. For most HVAC systems, sound sources are associated with the building's mechanical and electrical equipment. As shown in Figure 1, there are many possible paths for airborne and structureborne sound and vibration transmission between a sound source and receiver. It is not always possible for HVAC system designers to modify or change the sound source or receiver characteristics. Thus, system designers are most often constrained to modifying the sound and vibration transmission paths to achieve acceptable receiver sound levels in occupied areas of a building.

Different sources produce sounds that have different frequency distributions, called **spectral characteristics**. For example, as shown in Figure 2, fan noise generally contributes to sound levels in the 16 to 250 Hz octave bands (curve A). [Frequencies that designate the octave bands are often called **octave midband** (or **center**) **frequencies**.] Variable-air-volume (VAV) valve noise usually contributes to sound levels in the 63 to 1000 Hz octave bands (curve B). Diffuser noise usually contributes to the overall HVAC noise in the 250 to 8000 Hz octave bands (curve C). The overall sound pressure level associated with all of these sound sources combined is shown as curve D.
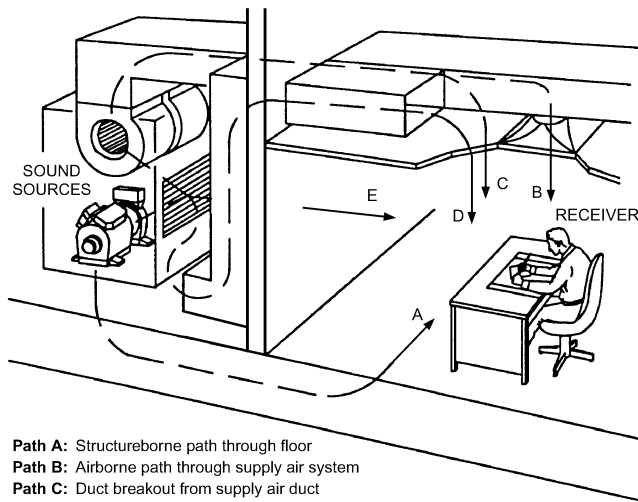
Path A: Structureborne path through floor
Path B: Airborne path through supply air system
Path C: Duct breakout from supply air duct
Path D: Airborne path through return air system
Path E: Airborne path through mechanical equipment room wall

Fig. 1   Typical Paths in HVAC Systems
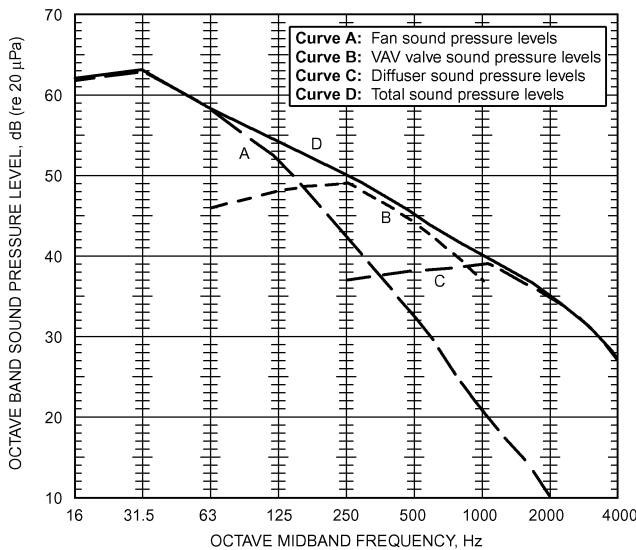
Fig. 2   Illustration of Well-Balanced HVAC Sound Spectrum for Occupied Spaces

Fig. 3   Frequency Ranges of Likely Sources of Sound-Related Complaints
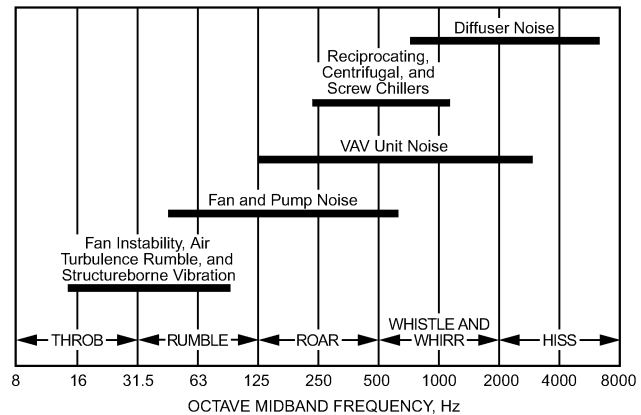
Fig. 4   Frequencies at Which Different Types of Mechanical Equipment Generally Control Sound Spectra

Occupants may complain when an acceptable sound spectrum is not achieved in an occupied space. Figure 3 (Schaffer 2005) shows the frequency ranges of the most likely sources of HVAC sound-related complaints. Figure 4 (Schaffer 2005) shows the frequencies at which different types of mechanical equipment generally control the sound spectra in a room. Occupant complaints may occur, however, despite a well-designed sound spectrum in the room. Criteria specified in this chapter do not necessarily correspond with all individuals' acceptability criteria.

BASIC ACOUSTICAL DESIGN TECHNIQUES

When selecting fans and other related mechanical equipment and when designing air distribution systems to minimize sound transmitted from system components to occupied spaces, consider the following:

• Design the air distribution system to minimize flow resistance and turbulence. High flow resistance increases required fan pressure, which results in higher noise being generated by the fan.

Turbulence increases flow noise generated by duct fittings and dampers, especially at low frequencies.

• Select a fan to operate as near as possible to its rated peak efficiency when handling the required airflow and static pressure. Also, select a fan that generates the lowest possible noise at required design conditions. Using an oversized or undersized fan that does not operate at or near rated peak efficiency can substantially increase noise levels.

• Design duct connections at both fan inlet and outlet for uniform and straight airflow. Both turbulence (at fan inlet and outlet) and flow separation at the fan blades can significantly increase fan-generated noise. Turning vanes near fan outlets can also increase turbulence and noise, especially if airflow is not sufficiently uniform.

• Select duct silencers that do not significantly increase the required fan total static pressure. Selecting silencers with static pressure losses of 0.35 in. of water or less can minimize regenerated noise from silencer airflow.

• Place fan-powered mixing boxes associated with variable-volume-air distribution systems away from noise-sensitive areas.

• Minimize flow-generated noise by elbows or duct branch takeoffs whenever possible by locating them at least four to five duct diameters from each other. For high-velocity systems, it may be necessary to increase this distance to up to 10 duct diameters in critical noise areas. Using flow straighteners or honeycomb grids, often called "egg crates," in the necks of short-length takeoffs that lead directly to grilles, registers, and diffusers is preferred to using volume extractors that protrude into the main duct airflow.

Table 1 Sound Sources, Transmission Paths, and Recommended Noise Reduction Methods

Sound Source	Path No.
Circulating fans; grilles; registers; diffusers; unitary equipment in room	1
Induction coil and fan-powered VAV mixing units	1, 2
Unitary equipment located outside of room served; remotely located air-handling equipment, such as fans, blowers, dampers, duct fittings, and air washers	2, 3
Compressors, pumps, and other reciprocating and rotating equipment (excluding air-handling equipment)	4, 5, 6
Cooling towers; air-cooled condensers	4, 5, 6, 7
Exhaust fans; window air conditioners	7, 8
Sound transmission between rooms	9, 10

No.	Transmission Paths	Noise Reduction Methods
1	Direct sound radiated from sound source to ear Reflected sound from walls, ceiling, and floor	Direct sound can be controlled only by selecting quiet equipment. Reflected sound is controlled by adding sound absorption to room and to equipment location.
2	Air- and structureborne sound radiated from casings and through walls of ducts and plenums is transmitted through walls and ceiling into room	Design duct and fittings for low turbulence; locate high-velocity ducts in noncritical areas; isolate ducts and sound plenums from structure with neoprene or spring hangers.
3	Airborne sound radiated through supply and return air ducts to diffusers in room and then to listener by Path 1	Select fans for minimum sound power; use ducts lined with sound-absorbing material; use duct silencers or sound plenums in supply and return air ducts.
4	Noise transmitted through equipment room walls and floors to adjacent rooms	Locate equipment rooms away from critical areas; use masonry blocks or concrete for mechanical equipment room walls; use floating floors in mechanical rooms.
5	Vibration transmitted via building structure to adjacent walls and ceilings, from which it radiates as noise into room by Path 1	Mount all machines on properly designed vibration isolators; design mechanical equipment room for dynamic loads; balance rotating and reciprocating equipment.
6	Vibration transmission along pipes and duct walls	Isolate pipe and ducts from structure with neoprene or spring hangers; install flexible connectors between pipes, ducts, and vibrating machines.
7	Noise radiated to outside enters room windows	Locate equipment away from critical areas; use barriers and covers to interrupt noise paths; select quiet equipment.
8	Inside noise follows Path 1	Select quiet equipment.
9	Noise transmitted to an air diffuser in a room, into a duct, and out through an air diffuser in another room	Design and install duct attenuation to match transmission loss of wall between rooms; use crosstalk silencers in ductwork.
10	Sound transmission through, over, and around room partition	Extend partition to ceiling slab and tightly seal all around; seal all pipe, conduit, duct, and other partition penetrations.

- Keep airflow velocity in ducts serving sound-sensitive spaces as low as possible by increasing the duct size to minimize turbulence and flow-generated noise (see Tables 3 and 4, in the section on Aerodynamically Generated Sound in Ducts).
- Duct transitions should not exceed an included expansion angle of 15°, or the resulting flow separation may produce rumble noise.
- Use turning vanes in large 90° rectangular elbows and branch takeoffs. This provides a smoother directional transition, thus reducing turbulence.
- Place grilles, diffusers, and registers into occupied spaces as far as possible from elbows and branch takeoffs.
- Minimize use of volume dampers near grilles, diffusers, and registers in acoustically critical situations.
- Vibration-isolate all reciprocating and rotating equipment connected to structure. Also, it is usually necessary to vibration-isolate mechanical equipment located in the basement of a building as well as piping supported from the ceiling slab of a basement, directly below tenant space. It may be necessary to use flexible piping connectors and flexible electrical conduit between rotating or reciprocating equipment and pipes and ducts that are connected to the equipment.
- Vibration-isolate ducts and pipes, using spring and/or neoprene hangers for at least the first 50 ft from vibration-isolated equipment.
- Use barriers near outdoor equipment when noise associated with the equipment will disturb adjacent properties. In normal practice, barriers typically produce no more than 15 dB of sound attenuation in the midfrequency range. To be effective, the noise barrier must at least block the direct "line of sight" between the source and receiver.

Table 1 lists several common sound sources associated with mechanical equipment noise. Anticipated sound transmission paths and recommended noise reduction methods are also listed. Airborne and/or structureborne sound can follow any or all of the transmission paths associated with a specified sound source. Schaffer (2005) has more detailed information in this area.

SOURCE SOUND LEVELS

Accurate acoustical analysis of HVAC systems depends in part on reliable equipment sound data. These data are often available from equipment manufacturers in the form of sound pressure levels at a specified distance from the equipment or, preferably, equipment sound power levels. Standards used to determine equipment and component sound data are listed at the end of this chapter.

When reviewing manufacturers' sound data, obtain certification that the data have been obtained according to one or more of the relevant industry standards. If they have not, the equipment should be rejected in favor of equipment for which data have been obtained according to relevant industry standards. See Ebbing and Blazier (1998) for further information.

Fans

Prediction of Fan Sound Power. The sound power generated by a fan performing at a given duty is best obtained from manufacturers' test data taken under approved test conditions (AMCA *Standard* 300 or ASHRAE *Standard* 68/AMCA *Standard* 330). Applications of air-handling products range from stand-alone fans to systems with various modules and attachments. These appurtenances and modules can have a significant effect on air-handler sound power levels. In addition, fans of similar aerodynamic performance can have significant acoustical differences.

Predicting air-handling unit sound power from fan sound levels is difficult. Fan sound determined by tests may be quite different once the fan is installed in an air handler, which in effect creates a new
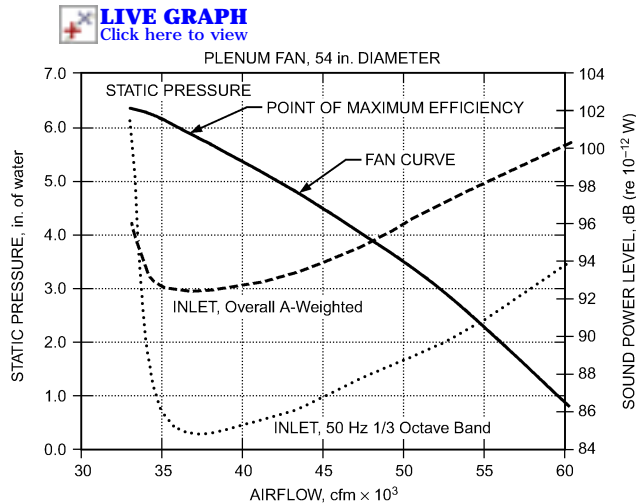
Note that A-weighted sound power level and 50 Hz 1/3 octave band sound power level rise as operating point moves away from maximum efficiency point.

Fig. 5   Test Data for Plenum Fan, Comparing Operating Point (Static Pressure and Airflow), A-Weighted Sound Power Level, and 50 Hz 1/3 Octave Sound Power Level

acoustical environment. Proper testing to determine resulting sound power levels once a fan is installed is essential. Fan manufacturers are in the best position to supply information on their products, and should be consulted for data when evaluating the acoustic performance of fans for an air handler application. Similarly, air handler manufacturers are in the best position to supply acoustic information on air handlers.

Air handler manufacturers typically provide discharge, inlet, and casing-radiated sound power levels for their units based on one of two methods. The most common method is the **fan-plus-algorithm** method: the fan is tested as a stand-alone item, typically using AMCA *Standard* 300, and an algorithm is used to predict the effect of the rest of the air-handling unit on the sound as it travels from the fan to the discharge and intake openings or is radiated through a casing with known transmission loss values. Another method is the **ARI 260** method, in which the entire unit is tested in accordance with ARI *Standard* 260. Under this standard, the entire unit is tested as an assembly, including fans, filters, coils, plenums, casing, etc., and the sound power level at the inlet and discharge openings, as well as the radiated sound power, is measured in a qualified reverberant room. Whenever possible, data obtained by the ARI 260 method should be used because it eliminates much of the uncertainty present in the **fan-plus-algorithm** method.

For a detailed description of fan operations, see Chapter 18 in the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*.

Different fan types have different noise characteristics and within a fan type, several factors influence noise.

Point of Fan Operation. The point of fan operation has a major effect on acoustical output. Fan selection at the calculated point of maximum efficiency is common practice to ensure minimum power consumption. In general, for a given design, fan sound is at a minimum near the point of maximum efficiency. Noise increases as the operating point shifts to the right, as shown in Figure 5 (higher airflow and lower static pressure). Low-frequency noise can increase substantially at operating points to the left (lower airflow and higher static pressure). These operating points should be avoided.

Blade-Pass Frequency. The blade-pass frequency is represented by the number of times per second a fans impeller passes a stationary item: f_{bp} = (rpm × number of impeller blades)/60. All fans generate a tone at this frequency and its multiples (harmonics). Whether this tone is objectionable or barely noticeable depends on the type and design of the fan and the point of operation.

Housed Centrifugal Fans. Forward-curved (FC) fans are commonly used in a wide range of standard air-handler products. The blade-pass of FC fans is typically less prominent and is at a higher frequency than other fans. The most distinguishing acoustical concern of FC fans is the prevalent occurrence of low-frequency rumble from airflow turbulence generated at blade tips, which can be exacerbated by nonideal discharge duct conditions (less than five diameters of straight duct). FC fans are commonly thought to have 16, 31.5, and 63 Hz (full octave band) rumble, particularly when operating to the left of the maximum efficiency point.

Backward-inclined (BI) fans and airfoil (AF) fans are generally louder at the blade-pass frequency than a given FC fan selected for the same duty, but are much more energy-efficient at higher pressures and airflow. The blade-pass tone generally increases in prominence with increasing fan speed and is typically in a frequency range that is difficult to attenuate. Below the blade-pass frequency, these fans generally have lower sound amplitude than FC fans and are often quieter at high frequencies.

Care should be taken with all types of housed fans to allow adequate clearance around the inlets. Also, note that belt guards both decrease airflow and increase sound generation.

Plenum Fans. A plenum fan has no housing around the fan impeller and discharges directly into the chamber, pressurizing the plenum, and forcing air through the attached ductwork. Air flows into the fan impeller through an inlet bell located in the chamber wall. These fans can substantially lower discharge sound power levels if the fan plenum is appropriately sized and acoustically treated with sound-absorptive material.

The plenum discharge should be located away from the fan's air blast, because blowing directly into the duct can aggravate the blade-pass sound. Avoid obstructing the inlet or crowding the coils or filters.

Vaneaxial Fans. Generally thought to have the lowest amplitudes of low-frequency sound of any of the fan types, axial fans are often used in applications where the higher-frequency noise can be managed with attenuation devices. In the useful operating range, noise from axial fans is a strong function of the inlet airflow symmetry and blade tip speed.

Propeller Fans. Sound from propeller fans generally has a low-frequency-dominated spectrum shape; the blade-pass frequency is typically prominent and occurs in the low-frequency bands because of the small number of blades. Propeller fan blade-pass frequency noise is very sensitive to inlet obstructions. For some propeller fan designs, the shape of the fan venturi (inlet) is also a very important parameter that affects sound levels. In some applications, noise of a propeller fan is described as sounding like a helicopter. Propeller fans are most commonly used on condensers and for power exhausts.

Minimizing Fan Sound. To minimize the required air distribution system sound attenuation, proper fan selection and installation are vital. The following factors should be considered:

• Design the air distribution system for minimum airflow resistance. High system resistance requires fans to operate at a higher brake horsepower, which generates higher sound power levels.

• Carefully analyze system pressure losses. Higher-than-expected system resistance may result in higher sound power levels than originally estimated.

• Examine the sound power levels of different fan types and designs. Select a fan (or fans) that generates the lowest sound power levels while meeting other fan selection requirements.

• Many fans generate tones at the blade-pass frequency and its harmonics that may require additional acoustical treatment of the system. Amplitude of these tones can be affected by resonance within the duct system, fan design, and inlet flow distortions caused by poor inlet duct design, or by operation of an inlet volume control damper. When possible, use variable-speed volume control instead of volume control dampers.

• Design duct connections at both fan inlet and outlet for uniform and straight airflow. Avoid unstable, turbulent, and swirling inlet airflow. Deviation from acceptable practice can severely degrade both aerodynamic and acoustic performance of any fan and invalidate manufacturers' ratings or other performance predictions.

Variable-Air-Volume (VAV) Systems

General Design Considerations. As in other aspects of HVAC system design, ducts for VAV systems should be designed for the lowest practical static pressure loss, especially ductwork closest to the fan or air-handling unit (AHU). High airflow velocities and convoluted duct routing with closely spaced fittings can cause turbulent airflow that results in excessive pressure drop and fan instabilities that can cause excessive noise, fan stall, or both.

Many VAV noise complaints have been traced to control problems. Although most problems are associated with improper installation, many are caused by poor design. The designer should specify high-quality fans or air handlers within their optimum ranges, not at the edge of their operation ranges where low system tolerances can lead to inaccurate fan flow capacity control. Also, in-duct static pressure sensors should be placed in duct sections having the lowest possible air turbulence (i.e., at least three equivalent duct diameters from any elbow, takeoff, transition, offset, or damper).

Balancing. VAV noise problems have also been traced to improper air balancing. For example, air balance contractors commonly balance an air distribution system by setting all damper positions without considering the possibility of reducing fan speed. The result is a duct system in which no damper is completely open and the fan delivers air at a higher static pressure than would otherwise be necessary. If the duct system is balanced with at least one balancing damper wide open, fan speed and corresponding fan noise could be reduced. Lower sound levels occur if most balancing dampers are wide open or eliminated. The specified goal should be to balance the system at the lowest static pressure required to operate the box located at the farthest point in the system.

Fan Selection. For constant-volume systems, fans should be selected to operate at maximum efficiency at design airflow. However, VAV systems must be selected to operate with efficiency and stability throughout the operating range. For example, a fan selected for peak efficiency at full output may aerodynamically stall at an operating point of 50% of full output, resulting in significantly increased low-frequency noise. A stalling fan can indicate operation in the **surge region**, a region of operational instability where airflow reverses direction at the fan blade because of insufficient air entering the fan wheel. Similarly, a fan selected to operate most efficiently at the 50% output point may be very inefficient at full output, resulting in substantially increased fan noise at all frequencies. In general, a fan for a VAV system should be selected for peak efficiency at an operating point between 70 and 80% of the maximum required system capacity, which is where the fan will operate most of the time. This usually means selecting a fan that is one size smaller than that required for peak efficiency at 100% of maximum required system capacity (Figure 6). When the smaller fan operates at higher capacities, it produces up to 5 dB more noise. This occasional increase in sound level is usually more tolerable than stall-related sound problems that can occur with a larger fan operating at less than 100% design capacity most of the time.

Air Modulation Devices. The control method selected to vary the air capacity of a VAV system is important. Variable-capacity control methods can be divided into three general categories: (1) variable inlet vanes (sometimes called inlet guide vanes) or discharge dampers that yield a new fan system curve at each vane or damper setting, (2) variable-pitch fan blades (usually used on axial fans) that adjust the blade angle for optimum efficiency at varying capacity requirements, and (3) variable-speed motor drives in which motor speed is varied by modulation of the power line frequency or by mechanical means such as gears or continuous belt adjustment.

Inlet vane and discharge damper volume controls can add noise to a fan system at reduced capacities, whereas variable-speed motor drives and variable-pitch fan blade systems are quieter at reduced air output than at full air output.

Variable-Inlet Vanes and Discharge Dampers. Variable-inlet vanes vary airflow capacity by changing inlet airflow to a fan wheel. This type of air modulation varies the total air volume and pressure at the fan, but fan speed remains constant. Although fan pressure and air volume reductions at the fan reduce duct system noise by reducing air velocities and pressures in the duct work, there is an associated increase in fan noise caused by airflow turbulence and flow distortions at the inlet vanes. Fan manufacturers' test data show that, on airfoil centrifugal fans, as vanes mounted inside the fan inlet (nested inlet vanes) close, the sound level at the blade-pass frequency of the fan increases by 2 to 8 dB, depending on the percent of total air volume restricted. For externally mounted inlet vanes, the increase is on the order of 2 to 3 dB. The increase for forward-curved fan wheels with inlet vanes is about 1 to 2 dB less than that for airfoil fan wheels. In-line axial fans with inlet vanes generate increased noise levels of 2 to 8 dB in the low-frequency octave bands for a 25 to 50% closed vane position.

Discharge dampers, typically located immediately downstream of the supply air fan, reduce airflow and increase pressure drop across the fan while fan speed remains constant. Because of air turbulence and flow distortions created by the high pressure drop across discharge dampers, there is a high probability of duct rumble near the damper location. If the dampers are throttled to a very low flow, a stall condition can occur at the fan, resulting in an increase in low-frequency noise.

Variable-Pitch Fans for Capacity Control. Variable-pitch fan blade controls vary the fan blade angle to reduce airflow. This type of system is predominantly used in axial fans. As air volume and pressure are reduced at the fan, there is a corresponding noise reduction. In the 125 to 4000 Hz octave bands, this reduction usually varies between 2 to 5 dB for a 20% reduction in air volume, and between 8 to 12 dB for a 60% reduction in air volume.

Variable-Speed Motor Controlled Fan. Three types of electronic variable-speed control units are used with fans: (1) current source inverter, (2) voltage source inverter, and (3) pulse-width modulation (PWM). The current source inverter and third-generation PWM control units are usually the quietest of the three controls. In all three types, matching motors to control units and the quality of the motor windings determine the motor's noise output. The motor typically emits a pure tone with an amplitude that depends on the smoothness of the waveform from the line current. The frequency of
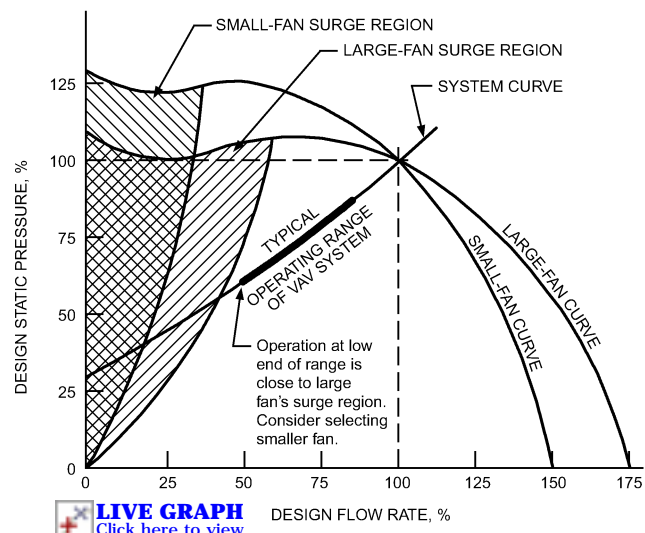
Fig. 6   Basis for Fan Selection in VAV Systems

the motor tone depends on the motor type, windings, and speed, but is typically at the drive's switching frequency. Some drives allow adjustment to a higher frequency that does not carry as well, but at a cost of lower drive efficiency. Both inverter control units and motors should be enclosed in areas, such as mechanical rooms or electrical rooms, where the noise effect on surrounding rooms is minimal. The primary acoustic advantage of variable-speed fans is reduction of fan speed, which translates into reduced noise; dB reduction is approximately equal to $50 \times \log$(higher speed/lower speed). Because this speed reduction generally follows the fan system curve, a fan selected at optimum efficiency initially (lowest noise) does not lose that efficiency as the speed is reduced. When using variable-speed controllers,

- Select fan vibration isolators on the basis of the lowest practical speed of the fan. For example, the lowest rotational speed might be 600 rpm for a 1000 rpm fan in a commercial system.
- Select a controller with a feature typically called "critical frequency jump band." This feature allows a user to program the controller to avoid certain fan or motor rpm settings that might excite vibration isolation system or building structure resonance frequencies, or correspond to speeds of other fans in the same system.
- Check the intersection of the fan's curve at various speeds against the duct system curve. When selecting a fan controlled by a variable-speed motor controller, keep in mind that the system curve does not go to zero static pressure at no flow. The system curve is asymptotic at the static pressure control set point, typically 1 to 1.5 in. of water. An improperly selected fan may be forced to operate in its stall range at slower fan speeds.

Terminal Units. Fans and pressure-reducing valves in VAV units should have manufacturer-published sound data indicating sound power levels that (1) are discharged from the low-pressure end of the unit and (2) radiate from the exterior shell of the unit. These sound power levels vary as a function of valve position and fan point of operation. Sound data for VAV units should be obtained according to the procedures specified by the latest ARI *Standard* 880. In critical situations, a mock-up test should be conducted of a production terminal box under project conditions and space finishes. The test is required because minor changes in box motor, fan, or valve components can affect the noise generated by such equipment.

If the VAV unit is located in noncritical areas (e.g., above a storeroom or corridor), sound radiated from the shell of the unit may be of no concern. If, however, the unit is located above a critical space and separated from the space by a ceiling with little or no sound transmission loss at low frequencies, sound radiated from the shell into the space below may exceed the desired noise criterion. In this case, it may be necessary to relocate the unit to a noncritical area or to enclose it with a high-transmission-loss construction. In general, fan-powered VAV units should not be placed above or near any room with a required sound criterion rating of less than RC 40(N) (Schaffer 2005). For further information, see the section on Indoor Sound Criteria.

Systems that allow use of VAV units that do not completely shut off are often helpful. If too many units in a system shut off simultaneously, excessive duct system pressure at low flow can occur. This condition can sometimes cause a fan to go into stall, resulting in accompanying roar, rumble, and surge. Using minimum-airflow instead of shutoff VAV units helps prevent this (Schaffer 2005).

Rooftop-Mounted Air Handlers

Rooftop air handlers can have unique noise control requirements because these units are often integrated into a lightweight roof construction. Large roof openings are often required for supply and return air duct connections. These ducts run directly from noise-generating rooftop air handlers to the building interior. Generally, there is insufficient space or distance between roof-mounted equipment and the closest occupied spaces below the roof to apply standard sound control treatments. Rooftop units should be located above
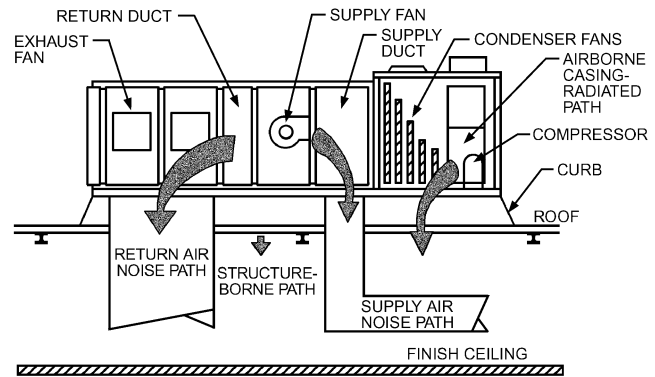
Fig. 7 Sound Paths for Typical Rooftop Installations

spaces that are not acoustically sensitive and should be placed as far as possible from the nearest occupied space. This measure can reduce the amount of sound control treatment necessary to achieve an acoustically acceptable installation.

The five common sound transmission paths associated with rooftop air handlers (Figure 7) are

- Airborne through bottom of rooftop unit to spaces below
- Structureborne from vibrating equipment in rooftop unit to building structure
- Ductborne through supply air duct from air handler
- Ductborne through return air duct to air handler
- Duct breakout noise (see the section on Sound Radiation Through Duct Walls)

Airborne paths are associated with casing-radiated sound that passes through the air-handler enclosure and roof structure to the spaces below. Airborne sound can result from air-handler noise or from other equipment components in the rooftop unit. Rooftop units should not be placed on open curbs or over a large opening in the roof structure through which both supply and return air ducts pass. Roof penetrations should be limited to two openings sized to accommodate only the supply and return air ducts. These openings should be properly sealed after installation of the ducts. If a large single opening exists under the rooftop unit, it should be structurally, acoustically, and flexibly sealed with one or more layers of gypsum board or other similar material around the supply and return air ducts. Airborne sound transmission to spaces below a rooftop unit can be greatly reduced by placing the rooftop unit on a structural support extending above the roof structure, and running supply and return air ducts horizontally along the roof for several duct diameters before the ducts turn to penetrate the roof. The roof deck/ceiling system below the unit can be constructed to adequately attenuate sound radiated from the bottom of the unit.

Using proper vibration isolation can minimize structureborne sound and vibration from vibrating equipment in a rooftop unit. Special curb mounting bases are available to support and provide vibration isolation for rooftop units. For roofs constructed with open web joists, thin long-span slabs, wooden construction, and any unusually light construction, evaluate all equipment weighing more than 300 lb to determine the additional deflection of the structure at mounting points caused by the equipment. Isolator deflection should be a minimum of 15 times the additional static deflection. If the required spring isolator deflection exceeds commercially available products, stiffen the supporting structure or change the equipment location.

Ductborne transmission of sound through the supply air duct consists of two components: sound transmitted from the air handler through the supply air duct system to occupied areas, and sound transmitted via duct breakout through a section or sections of the supply air duct close to the air handler to occupied areas. Sound

Table 2 Duct Breakout Insertion Loss—Potential Low-Frequency Improvement over Bare Duct and Elbow

Discharge Duct Configuration, 12 ft of Horizontal Supply Duct	Duct Breakout Insertion Loss at Low Frequencies, dB			Side View	End View
	63 Hz	125 Hz	250 Hz		
Rectangular duct: no turning vanes (reference)	0	0	0		
Rectangular duct: one-dimensional turning vanes	0	1	1		
Rectangular duct: two-dimensional turning vanes	0	1	1		
Rectangular duct: wrapped with foam insulation and two layers of lead	4	3	5		
Rectangular duct: wrapped with glass fiber and one layer 5/8 in. gypsum board	4	7	6		
Rectangular duct: wrapped with glass fiber and two layers 5/8 in. gypsum board	7	9	9		
Rectangular plenum drop (12 ga.): three parallel rectangular supply ducts (22 ga.)	1	2	4		
Rectangular plenum drop (12 ga.): one round supply duct (18 ga.)	8	10	6		
Rectangular plenum drop (12 ga.): three parallel round supply ducts (24 ga.)	11	14	8		
Rectangular (14 ga.) to multiple drop: round mitered elbows with turning vanes, three parallel round supply ducts (24 ga.)	18	12	13		
Rectangular (14 ga.) to multiple drop: round mitered elbows with turning vanes, three parallel round lined double-wall, 22 in. OD supply ducts (24 ga.)	18	13	16		
Round drop: radius elbow (14 ga.), single 37 in. diameter supply duct	15	17	10		

transmission below 250 Hz through duct breakout is often a major acoustical limitation for many rooftop installations. Excessive low-frequency noise associated with fan noise and air turbulence in the region of the discharge section of the fan (or air handler) and the first duct elbow results in duct rumble, which is difficult to attenuate. This problem is often worsened by the presence of a high-aspect-ratio duct at the discharge section of the fan (or air handler). Rectangular ducts with duct lagging are often ineffective in reducing duct breakout noise. Using either a single- or dual-wall round duct with a radiused elbow coming off the discharge section of the fan can reduce duct breakout. If space does not allow for the use of a single duct, the duct can be split into several parallel round ducts. Another effective method is using an acoustic plenum chamber constructed of a minimum 2 in. thick, dual-wall plenum panel, lined with fiberglass and with a perforated inner liner, at the discharge section of the fan. Either round or rectangular ducts can be taken off the plenum as necessary for the rest of the supply air distribution system. Table 2 illustrates 12 possible rooftop discharge duct configurations with their associated low-frequency noise reduction potential (Beatty 1987; Harold 1986, 1991).

Ductborne transmission of sound through the return air duct of a rooftop unit is often a problem because there is generally only one short return air duct section between the plenum space above a ceiling and the return air section of the air handler. This does not allow for adequate sound attenuation between the fan inlet and spaces below the air handler. Sound attenuation through the return air duct system can be improved by adding at least one (more if possible) branch division where the return air duct is split into two sections that extend several duct diameters before they terminate into the plenum space above the ceiling. The inside surfaces of all return air ducts should be lined with a minimum of 1 in. thick duct liner. If conditions permit, duct silencers in duct branches or an acoustic plenum chamber at the air-handler inlet section give better sound conditions.

Aerodynamically Generated Sound in Ducts

Aerodynamic sound is generated when airflow turbulence occurs at duct elements such as duct fittings, dampers, air modulation units,

Table 3   Maximum Recommended Duct Airflow Velocities to Achieve Specified Acoustic Design Criteria

Main Duct Location	Design RC(N)	Maximum Airflow Velocity, fpm	
		Rectangular Duct	Circular Duct
In shaft or above drywall ceiling	45	3500	5000
	35	2500	3500
	25	1700	2500
Above suspended acoustic ceiling	45	2500	4500
	35	1750	3000
	25	1200	2000
Duct located within occupied space	45	2000	3900
	35	1450	2600
	25	950	1700

Notes:
1. Branch ducts should have airflow velocities of about 80% of values listed.
2. Velocities in final runouts to outlets should be 50% of values or less.
3. Elbows and other fittings can increase airflow noise substantially, depending on type. Thus, duct airflow velocities should be reduced accordingly.

Table 4   Maximum Recommended Air Velocities at Neck of Supply Diffusers or Return Registers to Achieve Specified Acoustical Design Criteria

Type of Opening	Design RC(N)	"Free" Opening Airflow Velocity, fpm
Supply air outlet	45	625
	40	560
	35	500
	30	425
	25	350
Return air opening	45	750
	40	675
	35	600
	30	500
	25	425

Note: Table intended for use when no sound data are available for selected grilles or diffusers, or no diffuser or grille is used. The number of diffusers or grilles increases sound levels, depending on proximity to receiver. Allowable outlet or opening airflow velocities should be reduced accordingly in these cases.

sound attenuators, and room air devices. For details on air modulation units and sound attenuators, see the sections on Variable Air Volume Systems and Duct Silencers.

Although fans are a major source of sound in HVAC systems, aerodynamically generated sound can often exceed fan sound because of close proximity to the receiver. When making octave-band fan sound calculations using a source-path-receiver analysis, aerodynamically generated sound must be added in the path sound calculations at the location of the element.

Duct Velocities. The extent of aerodynamic sound is related to the airflow turbulence and velocity through the duct element. The sound amplitude of aerodynamically generated sound in ducts is proportional to the fifth, sixth, and seventh power of the duct airflow velocity in the vicinity of a duct element (Bullock 1970; Ingard et al. 1968). Therefore, reducing duct airflow velocity significantly reduces flow-generated noise. Tables 3 (Schaffer 2005) and 4 (Egan 1988) give guidelines for recommended airflow velocities in duct sections and duct outlets to avoid problems associated with aerodynamically generated sound in ducts.

Fixed Duct Fittings. Fixed duct fittings include elbows, tees, transitions, fixed dampers, and branch takeoffs. In all cases, less generated air turbulence and lower airflow velocities result in less aerodynamic sound. Figures 8 and 9 show typical frequency spectra for specific sizes of elbows and transitions. Data in these figures are based on empirical data obtained from ASHRAE RP-37 (Ingard et al. 1968). Normalized data from ASHRAE RP-37 and others, which can apply to all types of duct fittings and dampers, have been
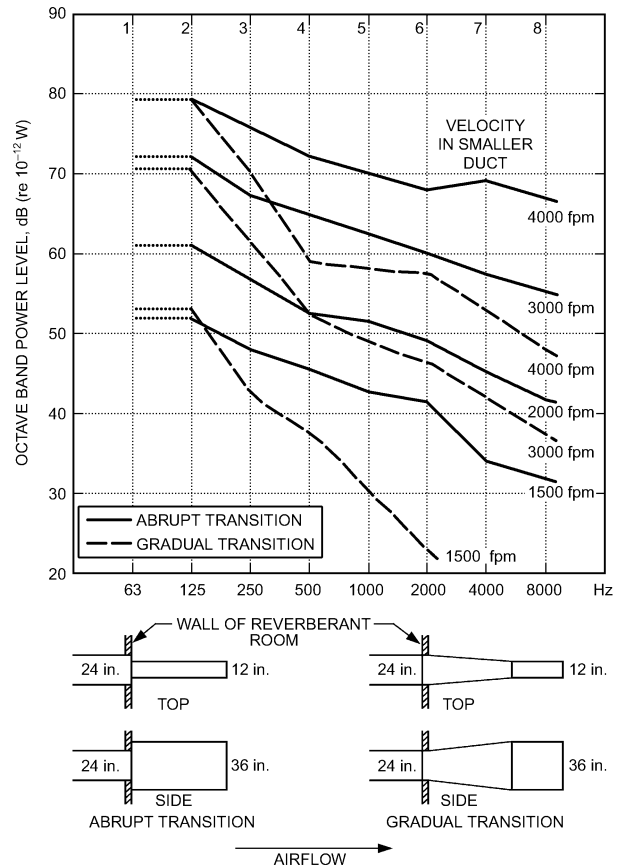
Fig. 8   Velocity-Generated Sound of Duct Transitions

published (Bullock 1970) and presented in ASHRAE RP-265 (Ver 1983a). When multiple duct fittings are installed adjacent to each other, aerodynamic sound can increase significantly because of the added air turbulence and increased velocity pressures. Note that the magnitude of the field-measured static pressure drop across fixed duct fittings does not relate to the aerodynamic generated sound. However, total pressure drop across a duct fitting, which includes the velocity pressure change resulting from air turbulence, does affect aerodynamically generated sound.

Operable Volume Dampers. Operable damper aerodynamic sound is created because the damper is an obstacle in the airstream, and air turbulence increases as the damper closes. Because total pressure drop across the damper also increases with closure, the aerodynamic sound is related to the total pressure drop. Both single-blade and multiblade dampers, used to balance and control the airflow in a duct system and at room air devices, have similar frequency spectra. Figure 10 shows the frequency spectrum for a 45° damper in a 24 by 24 in. duct (Ingard et al. 1968).

Depending on its location relative to a room air device, a damper can generate sound that is transmitted down the duct to the room air device, or radiate sound through the ceiling space into the occupied space below. When an operable control damper is installed close to an air device to achieve system balance, the acoustic performance of the air outlet must be based not only on the air volume handled, but also on the magnitude of the air turbulence generated at the damper. The sound level produced by closing the damper is accounted for by adding a correction to the air device sound rating. As the damper is modulated for air balance, this quantity is proportional to the pressure ratio (PR), that is, the throttled total pressure drop across the damper divided by the minimum total pressure drop across the damper. Table 5 provides decibel corrections to determine the effect of damper location on linear diffuser sound ratings.
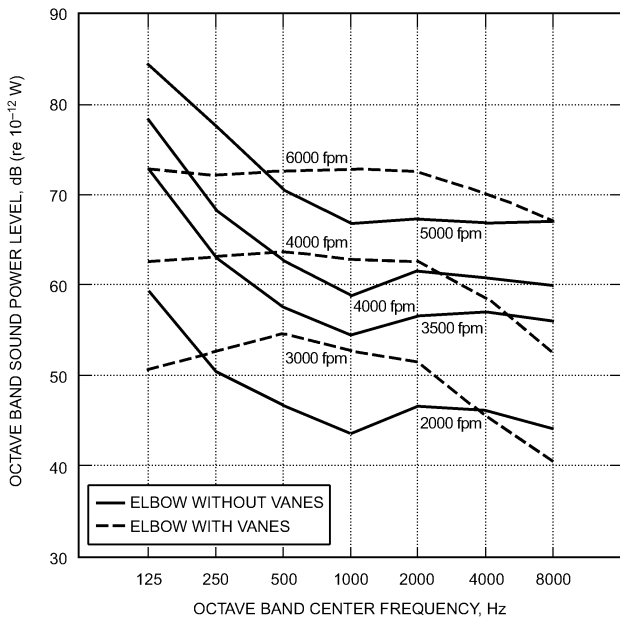
Note: Comparison of octave band sound power levels produced by airflow through 8 × 8 in. rectangular elbow with and without 7 circular arc turning vanes.

Fig. 9   Velocity-Generated Sound of Elbows
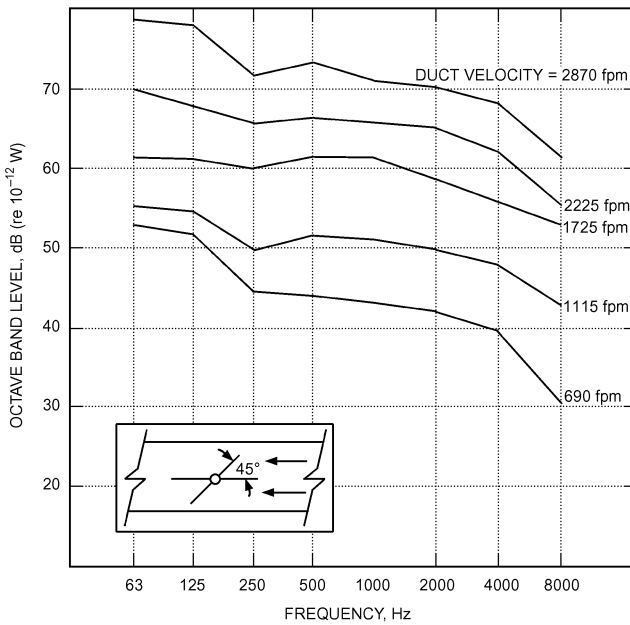
Fig. 10   Velocity-Generated Sound of 24 by 24 in. Volume Damper

Table 5   Decibels to Be Added to Diffuser Sound Rating to Allow for Throttling of Volume Damper

Location of Volume Damper	Damper Pressure Ratio					
	1.5	2	2.5	3	4	6
	dB to Be Added to Diffuser Sound Rating					
In neck of linear diffuser	5	9	12	15	18	24
In inlet of plenum of linear diffusers	2	3	4	5	6	9
In supply duct at least 5 ft from inlet plenum of linear diffuser	0	0	0	2	3	5

Volume dampers in sound-critical spaces should always be a minimum of 5 to 10 duct diameters from air device, with an acoustically lined duct between the damper and air device. Acoustically lined plenums may also be used between the damper and room air device to reduce damper sound. Linear air devices with a round duct connected to an insulated plenum have been successfully used for damper sound control. However, acoustical lining in this type of plenum does not minimize the sound generated by air flowing through a short section of the linear air device. If multiple inlets/outlets are used to spread airflow uniformly over the lined plenum and air device, then the linear slot generates less sound.

Proper air balancing of a fan/duct system directly affects aerodynamically generated sound even in a correctly designed and installed duct system. Primary volume dampers in the longest duct from a fan should always be nearly wide-open. If the primary damper in the longest duct run is more than 20% closed, the duct system has not been properly air balanced, and the fan may operate at a higher speed than required for the duct system. The result is an increase in air velocities and turbulence throughout the entire duct system, with excessive aerodynamic sound generated at all duct elements.

Room Air Devices (Grilles, Registers, Diffusers). Manufacturers' test data should be obtained in accordance with ASHRAE *Standard* 70 or ARI *Standard* 890 for room air devices such as grilles, registers, diffusers, air-handling light fixtures, and air-handling suspension bars. Devices should be selected to meet the noise criterion required or specified for the room. However, the manufacturer's sound power rating is obtained with a uniform velocity distribution throughout the air device neck or grille collar; this is often not met in practice when a duct turn, sharp transition, or a balancing damper immediately precedes the entrance to the diffuser. In these cases, airflow is turbulent and noise generated by the device can be substantially higher than the manufacturer's published data (by as much as 12 dB). In some cases, placing an equalizer grid in the neck of the air device can substantially reduce this turbulence. The equalizer grid can help provide a uniform velocity gradient within the neck of the device, so the sound power generated in the field will be closer to that listed in the manufacturer's catalog.

At present, air devices are rated by manufacturers in terms of noise criterion (NC) levels, which usually includes a receiver room effect sound correction of 10 dB. The NC ratings may be useful for comparison between different air devices, but are not helpful for source-path-receiver calculations in terms of octave bands. For a complete analysis, the designer should request the component sound power level data in octave bands from the manufacturer. Whether using NC levels or sound power levels, the designer should also correct manufacturer's data for actual room effect, location of air devices, and number of air devices used in a specific design. The acoustical room effect is the reduction in sound level caused by distance from the sound source (e.g., air outlet); the room volume and amount of acoustical absorption present also affect the value. For more information, see the section on Receiver Room Sound Correction. For example, in a small room with an actual calculated room effect of 6 dB, and given a manufacturer's room effect correction of 10 dB, the discrepancy (in this case, 4 dB) must be added to the manufacturer's data. When an air device is located at the intersection of the ceiling and vertical wall, 6 dB should be added, and in the corner of a room, 9 dB should be added to manufacturer's data. When multiple room air devices are located in a small room or grouped together in a large room, the sound of air devices is additive by up to $10 \times \log$(number of air devices).

A flexible duct connection between a branch air duct and an air device provides a convenient means to align the air device with the ceiling grid. The resulting misalignment in this connection, as shown in Figure 11, can cause as much as 12 to 15 dB higher sound levels in the air device's aerodynamically generated sound.
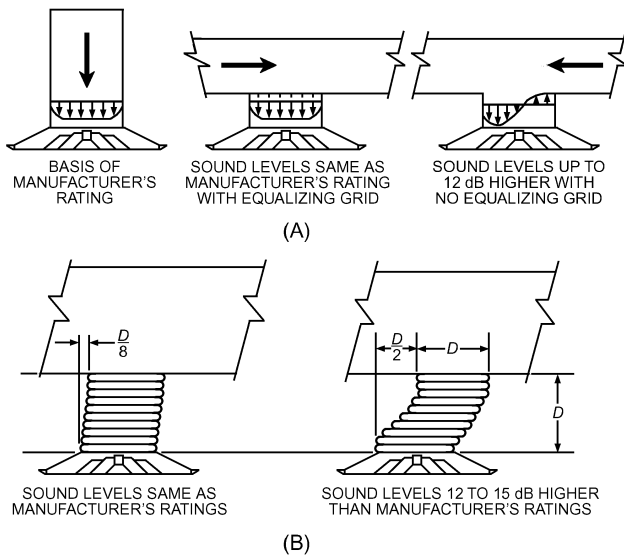
Fig. 11   **(A) Proper and Improper Airflow Condition to an Outlet; (B) Effect of Proper and Improper Alignment of Flexible Duct Connector**

Fig. 12   **Typical Minimum and Maximum ARI 575 L_p Values for Centrifugal Chillers (130 to 1300 Tons)**

Avoiding Aerodynamically Generated Noise. Aerodynamic noise in duct systems can be avoided by

- Sizing ductwork and duct elements for low air velocities
- Avoiding abrupt changes in duct cross-sectional area or direction
- Providing smooth airflow at all duct elements, including branches, elbows, tees, transitions, and room air devices
- Providing straight ductwork (preferably 5 to 10 duct diameters) between duct elements
- Air-balancing duct system for lowest reasonable fan speed with dampers generally open
- Locating volume control dampers a minimum of 3 (preferably 5 to 10) duct diameters away from room air devices (Schaffer 2005)

Compressors, Chillers, and Air-Cooled Condensers

All chillers and their associated systems produce significant amounts of both broadband and tonal noise. The broadband noise is caused by flows of both refrigerant and water, whereas the tonal noise is caused by rotation of compressors, motors, and fans (in fan-cooled equipment). Chiller noise is usually significant in the octave bands from 250 to 1000 Hz.

Noise Sources from Compressors and Chillers. All compressors, except absorption, produce tonal noise. Acoustical differences among compressors generally relate to their tonal content:

- **Centrifugal compressor** tonal noise comes from rotation of the impeller and gears in geared machines. Their tonal content is typically not very strong. However, centrifugal compressor sound pressure level (L_p) values typically increase at reduced chiller capacity because of the extra turbulence induced in the refrigerant circuit by inlet vanes. If capacity is reduced using motor speed control, the resulting compressor L_p values decrease with decreasing capacity.
- **Reciprocating compressor** noise has a drumming quality, caused by the oscillating motion of pistons. The tonal content is high and sound level decreases very little with decreasing capacity.
- **Absorption chillers** produce relatively little noise themselves, but the flow of steam in associated pumps and valves causes significant high-frequency noise. Noise levels increase with decreasing capacity as valves close. Also, combustion air blowers on direct gas-fired units can be noisy.
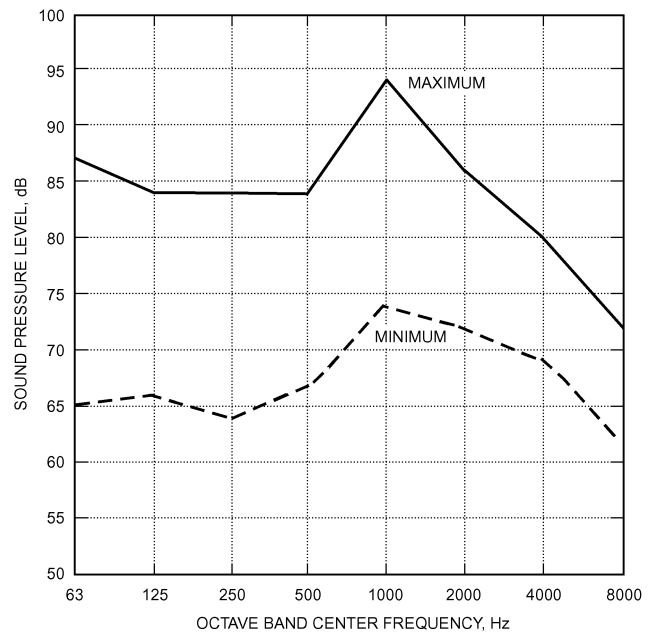
- **Scroll compressors** have relatively weak tones; in capacities less than 75 tons, they may not cause noise-related complaints.
- **Screw compressors** (sometimes called helical rotor or rotary compressors) have very strong tones in the 250 to 2000 Hz octave bands. Rotor-induced tones are amplified by resonances in the oil separation circuit and by efficient sound radiation by the condenser and evaporator shells that are rigidly connected to the compressor by high-pressure piping. Screw compressors have been the sources of chiller noise complaints; therefore, this type of compressor requires the most attention during noise and vibration control design.

Indoor Water-Cooled Chillers. The dominant noise source in water-cooled chillers is the compressor, which is most often a centrifugal or screw compressor.

Factory sound data for indoor chillers are obtained using ARI *Standard* 575, which requires measuring the A-weighted and octave band sound pressure level (L_p) values at several locations 3.28 ft from the chiller and 4.92 ft above the floor. ARI 575 sound pressure levels are generally available at operating points of 25, 50, and 100% of a chiller's nominal full capacity. The ranges of ARI 575 values for typical centrifugal and screw chillers are shown in Figures 12 and 13, respectively.

ARI 575 measurements are usually made in very large rooms with large amounts of sound absorption. Measured levels must be adjusted for each chiller installation to account for the mechanical room's size and surface treatment. For a given chiller at a given operating point, a small equipment room, or one with mostly hard surface finishes, has higher L_p values than one that is large or has sound-absorbing treatments on its ceiling and walls. Figure 14 shows maximum typical adjustment factors that should be added to factory-provided ARI 575 values to estimate reverberant L_p values in specific installations. The adjustment for each octave band requires knowing the size of an imaginary box that is circumscribed 3.28 ft away from the top and sides of the chiller (the ARI 575 measurement surface), the dimensions of the equipment room, and the average sound absorption coefficient of the room surfaces. The adjustment in each octave band depends on the ratio of the areas of the equipment room and the imaginary box as well as the average sound absorption of the room finishes. Each curve in Figure 14 is for a
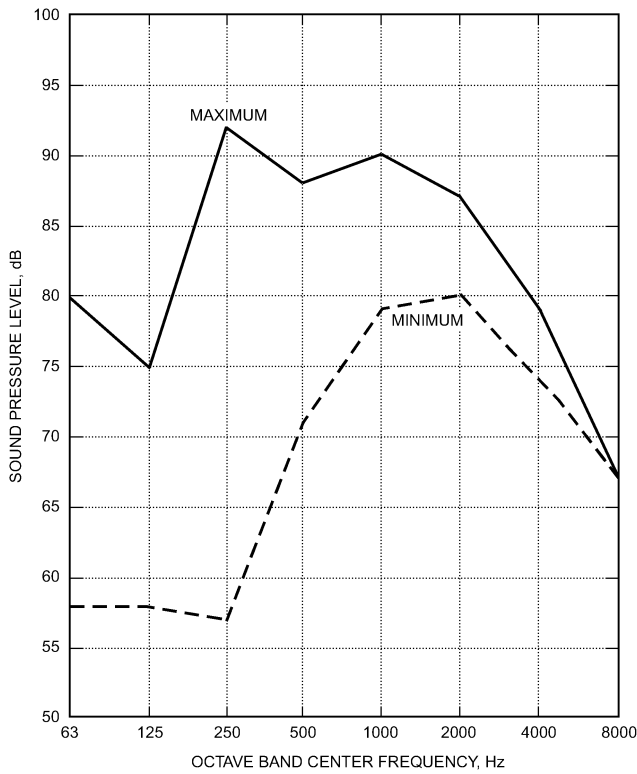
Fig. 13   Typical Minimum and Maximum ARI 575 L_p Values for Screw Chillers (130 to 400 Tons)

Fig. 14   Estimated Sound Level Build-Up in Mechanical Room for ARI 575 Chiller Sound Levels

different value of the average sound absorption, with the higher curves being for lower values.

Example 1. Estimate the reverberant L_p values in a 45 by 40 by 20 ft tall mechanical equipment room (MER) that houses a 360 ton centrifugal chiller. The room has a concrete floor and gypsum board walls and ceiling; all surfaces have an average absorption coefficient of 0.1. The chiller dimensions are 60 in. wide, 80 in. tall, and 120 in. long.

Solution:

The ARI 575 measurement surface area S_M is determined by adding 3.28 ft to the chiller height and 6.56 ft to both its length and width. The floor area is not included in this calculation. The result is a box that has dimensions of 140 in. wide, 200 in. long and 120 in. tall. The surface area of this box is approximately 751 ft². The surface area of the equipment room (floor included) S_R is 7000 ft². Therefore, the ratio of the areas S_R/S_M is 7000/751 = 9.3. Because the average absorption coefficient value for room is 0.1 for all octave bands, see Figure 14 for the adjustment factor and Table 6 for calculations.

The approximate reverberant L_p values in the last line of Example 1 can be used with sound transmission loss data of the construction to estimate transmitted L_p values in rooms adjacent to a chiller room.

Indoor chillers are offered with various types of factory noise reduction options for the compressor ranging from compressor blankets (A-weighted noise reduction of 2 to 6) to steel panel enclosures with sound-absorbing inner surfaces (A-weighted noise reduction up to 18). The amount of compressor noise reduction is limited because of structure-borne transmission of compressor vibration into the equipment frame and heat exchanger shells, which act as sounding boards. Most of these options for noise control only reduce tonal characteristics of compressor noise and may not reduce the overall sound power level.

Field noise control options include full-sized sheet metal housing with specially treated openings for piping, electrical conduit, and ventilation. Sometimes upgraded building construction is
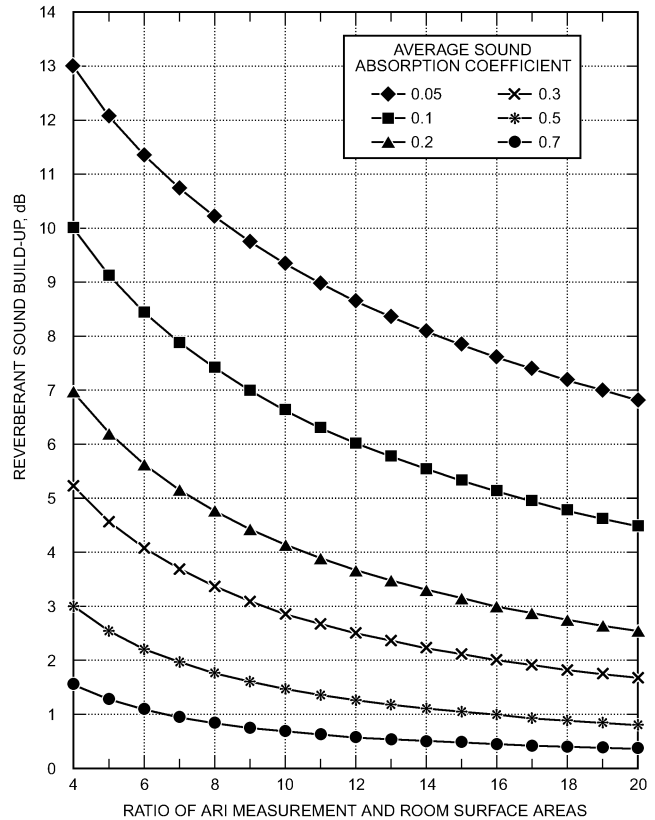
Table 6   Calculations for Reverberation Build-Up

	Octave Midband Frequency, Hz							
	63	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
ARI 575 L_p values	73	74	73	72	74	72	69	63
Adjustment from Figure 14	7	7	7	7	7	7	7	7
Approximate revised L_p in MER	80	81	80	79	81	79	76	70

necessary. For more information refer to the section on Mechanical Equipment Room Sound Isolation.

Outside Air-Cooled Chillers and Air-Cooled Condensers. These units often use either reciprocating, scroll, or screw compressors. They are also used as the chiller portion of rooftop packaged units. The dominant noise sources in outdoor air-cooled chillers are the compressors and the condenser fans, which are typically low-cost, high-speed propeller fans. For air-cooled condensing units, propeller fans are the only significant noise source.

Factory sound data for outdoor equipment are obtained in accordance with ARI *Standard* 370, which requires the determination of the equipment's octave band sound power levels (L_w), A-weighted sound power level (L_{wa}), and tone-adjusted A-weighted sound power level (L_{wat}). The range of ARI 370 L_w values for outdoor chillers in the 20 to 380 ton range is given in Figure 15.

Factory-supplied noise reduction options for outdoor equipment include compressor enclosures, oversized condenser fans, and variable-speed condenser fans. Because air-cooled equipment needs a free flow of cooling air, full enclosures are not feasible; however, strategically placed barriers can help reduce noise propagation on a selective basis. For more information, see the section on Sound Control for Outdoor Equipment.
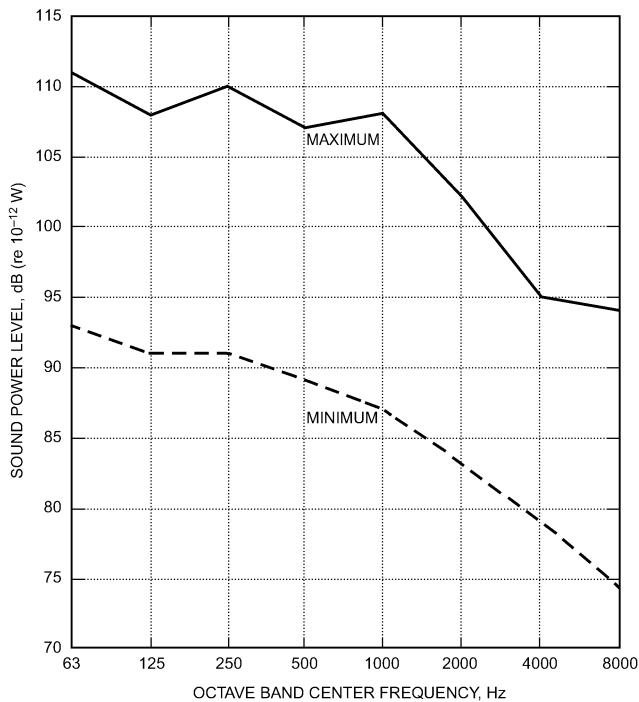
Fig. 15 Typical ARI 370 L_w Values for Outdoor Chillers (20 to 380 Tons)

Typical chilled-water systems include not only compressors and fans but also water pumps. The associated piping and conduit vibration generated by compressors and pumps can be transmitted to a building structure through equipment mounts or attachments of piping/conduit. Therefore, vibration isolation of chiller systems requires essentially floating the entire chiller water system on resilient floor mounts and hangers. See the section on Vibration Isolation and Control for more information on chiller system vibration control.

If a chiller is to be mounted on an on-grade slab, vibration isolators might not be required unless there are nearby noise-sensitive spaces. In noise-sensitive applications (e.g., rooftop chillers over occupied spaces), high-deflection springs or air mounts are likely to be required. Potential problems common to all steel spring and rubber pad vibration isolators are wave resonances, phenomena that occur at the natural frequencies of the isolators alone. These are particularly of concern in screw chiller applications because compressor tones typically occur in the same frequency region as the isolator's wave resonances. If one of the compressor tones happens to coincide with one of the isolator resonances, the compressor tone can be readily transmitted into the building structure, causing excessive structure-borne noise in occupied space near the unit. It is essentially impossible to predict this occurrence in advance; if it does happen, use either another isolator design (with different natural frequencies) or air mounts, which do not exhibit the natural frequency phenomenon.

Emergency Generators

Emergency or standby generators create very high sound levels and require special consideration, especially if used inside an occupied building. The primary noise sources include the engine casing, radiator, and engine exhaust, and must be considered separately if the generator is installed inside a building. Sound power levels for these units depend on the power rating, fuel type, engine speed, muffler design, and radiator system. Overall sound power levels can be as high as 130 dBA (re 10^{-12} W) for larger (1.5 to 2.0 MW) diesel-powered units with standard mufflers. Noise levels inside generator rooms almost always exceed 100 dBA if the power rating of the unit is greater than 50 kW.

Noise from the generator casing is broadband with a relatively uniform spectrum. Octave band noise data are usually available from the generator manufacturer. Casing noise does not vary much with load. Conversely, exhaust noise typically contains strong tones at the engine shaft's running frequency and at the engine firing rate. Standard engine exhaust mufflers reduce exhaust noise by 20 to 25 dBA (compared to unsilenced exhaust), but even with this noise reduction, strong tones still radiate from the exhaust outlet in most cases. High-performance (critical and supercritical grade) mufflers are available but are larger and more expensive than standard units. Exhaust pipes should be routed away from noise-sensitive areas, and the exhaust outlet should be located and oriented to ensure that community noise levels are not excessive. In occupied buildings, the entire exhaust pipe should be suspended from the structure above with spring hangers.

Engine casing noise is best controlled by enclosing the generator in a concrete enclosure. The biggest problem with generator room design is finding adequate space for ventilation air. Generators require a substantial volume of air for engine cooling, and controlling engine noise transmission using air intake and exhaust paths can be difficult. In most cases, air intake and exhaust openings require sound attenuators. Because engine radiators usually use propeller fans to move air across the radiator core, the ventilation system cannot always handle the added pressure drop created by sound attenuators. In some cases, auxiliary fans are needed to draw fresh air into the generator room through the intake silencers. Sound attenuators at the discharge opening should be located between the radiator and exhaust louver. A smooth, slowly expanding transition duct is required between the radiator and the discharge louver. Nonsymmetrical transitions and transitions with expansion angles greater than 15° usually result in nonuniform airflow through the sound attenuators, causing a higher-than-expected pressure drop and reduced airflow. Unless careful space planning is done early in the design phase, there is often not enough space in the generator room to fit the sound attenuators with a proper transition fitting.

Emergency generator radiator fans usually make as much or more noise than the engine casing; in noise-sensitive installations, a remote radiator should be considered. Most manufacturers offer remote radiators as an option, available in a wide variety of designs and noise levels. Lower sound levels with remote radiators are usually achieved by using larger fans running at lower speeds. Using a remote radiator can often save substantial expense in noise-sensitive applications because airflow requirements in the generator room are dramatically reduced.

PATH NOISE ESTIMATION AND CONTROL

Duct Element Sound Attenuation

A major transmission path of noise from mechanical equipment is through air distribution ductwork. Duct elements and concepts covered in this section include plenums, unlined rectangular ducts, acoustically lined rectangular ducts, unlined round ducts, acoustically lined round ducts, elbows, acoustically lined round radiused elbows, duct silencers, duct branch power division, duct end reflection loss, and terminal volume regulation units. Simplified tabular procedures for obtaining the sound attenuation associated with these elements are presented.

Plenums. Plenums are often placed between the outlet of a fan and main air distribution ducts to smooth turbulent airflow. These chambers are typically lined with acoustically absorbent material to reduce fan and other mechanical noise. Plenums are usually large rectangular enclosures with an inlet and one or more outlets.

Based on experience, ASHRAE-sponsored research (Mouratidis and Becker 2004), and earlier work (Wells 1958), transmission loss associated with a plenum can be expressed using the following considerations:

• Frequency range (above versus below the cutoff frequency)
• In-line inlet and outlet openings (no offset angle)

- End-in/end-out versus end-in/side-out orientation (i.e., in-line versus elbow configuration)

Above the cutoff frequency, as defined by the plenum's inlet duct dimensions, the wavelength of sound is small compared to the characteristic dimensions of the plenum. Plane wave propagation in a duct exists at frequencies below the cutoff, creating a need to consider two frequency ranges, where

$$f_{co} = \frac{c}{2a} \qquad (1)$$

or

$$f_{co} = 0.586\frac{c}{d} \qquad (2)$$

where

f_{co} = cutoff frequency, Hz
c = speed of sound in air, ft/s
a = larger cross-sectional dimension of rectangular duct, ft
d = diameter of round duct, ft

The cutoff frequency f_{co} is the frequency above which plane waves no longer propagate in a duct. At these higher frequencies, waves that propagate in the duct are called **cross** or **spinning modes**. The transmission loss (TL) in this higher frequency range may be predicted using the following relationship:

$$TL = b\left[\frac{S_{out}Q}{4\pi r^2} + \frac{S_{out}(1 - \alpha_a)}{S\alpha_a}\right]^n \qquad (3)$$

$$TL = b(K_f)^n \qquad (4)$$

where

TL = transmission loss, dB
b = 3.505
n = –0.359
K_f = attenuation coefficient
S_{out} = area of plenum outlet, ft^2
S = total inside surface area of plenum minus inlet and outlet areas, ft^2
r = distance between centers of inlet and outlet of plenum, ft
Q = directivity factor; taken as 2 for opening near center of wall, or 4 for opening near corner of plenum
α_a = average absorption coefficient of plenum lining [see Equation (5)]

The average absorption coefficient α_a of plenum lining is given by

$$\alpha_a = \frac{S_1\alpha_1 + S_2\alpha_2}{S_1 + S_2} \qquad (5)$$

where

α_1 = sound absorption coefficient of any bare or unlined inside surfaces of plenum
S_1 = surface area of any bare or unlined inside surfaces of plenum, ft^2
α_2 = sound absorption coefficient of acoustically lined inside surfaces of plenum
S_2 = surface area of acoustically lined inside surfaces of plenum, ft^2

In many situations, inside surfaces of a plenum chamber are lined with a sound-absorbing material. For these situations, $\alpha_a = \alpha_2$. Table 7 gives sound absorption coefficients for selected common plenum materials.

For lower frequencies that correspond to plane wave propagation in the duct, the following relationship applies, with a frequency limit of 50 Hz:

Table 7 Sound Absorption Coefficients α of Selected Plenum Materials

	Octave Midband Frequency, Hz						
	63	**125**	**250**	**500**	**1000**	**2000**	**4000**
Non-sound-absorbing material							
Concrete	0.01	0.01	0.01	0.02	0.02	0.02	0.03
Bare sheet metal	0.04	0.04	0.04	0.05	0.05	0.05	0.07
Sound-absorbing material (fiberglass insulation board)							
1 in., 3.0 lb/ft^3	0.05	0.11	0.28	0.68	0.90	0.93	0.96
2 in., 3.0 lb/ft^3	0.10	0.17	0.86	1.00	1.00	1.00	1.00
3 in., 3.0 lb/ft^3	0.30	0.53	1.00	1.00	1.00	1.00	1.00
4 in., 3.0 lb/ft^3	0.50	0.84	1.00	1.00	1.00	1.00	0.97

Note: 63 Hz values estimated from higher-frequency values.
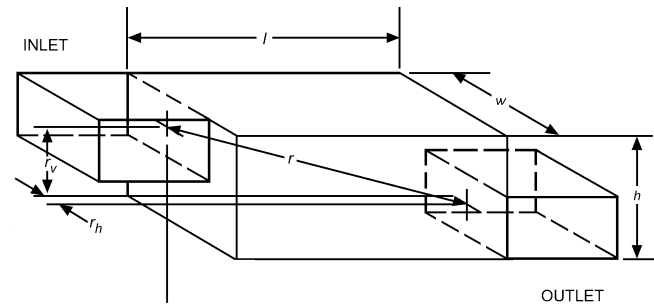
Fig. 16 Schematic of End-In/End-Out Plenum

$$TL = A_f S + W_e \qquad (6)$$

where

A_f = surface area coefficient, dB/ft^2 (see Table 8 for small and large plenum size ranges)
W_e = wall effect, dB (see Table 8 for common HVAC plenum wall types)

For an end-in/end-out plenum configuration, where the openings are not in-line, the offset angle θ must be considered in the TL calculation. The value of θ is obtained from the following relationship:

$$\cos\theta = \frac{l}{r} = \frac{l}{\sqrt{l^2 + r_v^2 + r_h^2}} \qquad (7)$$

where (refer to Figure 16)

θ = offset angle representing r to long axis l of duct
l = length of plenum, ft
r_v = vertical offset between axes of plenum inlet and outlet, ft
r_h = horizontal offset between axes of plenum inlet and outlet, ft

For a given offset angle, apply the applicable effects on TL (decibel addition or subtraction) for angles up to 45° (Table 9).

For an end-in/side-out plenum configuration, where openings are perpendicular to each other, the elbow effect must be considered in the TL calculation. For any plenum configuration involving an elbow condition, apply the applicable effects on TL (decibel addition or subtraction) for the two frequency ranges, both above and below the cutoff (Table 10).

For plenum applications within a practical size envelope of 20 to 1100 ft^3 volume or 50 to 650 ft^2 surface area, using duct sizes in the range $12 < d < 48$ in., this model may be applied with an anticipated standard deviation of ±3.5 to 5.0 dB for 50 Hz $< f \le f_c$ and ±1.5 to 3.0 for $f_c < f \le 5000$ Hz . Use caution when applying these prediction methods for plenum configurations where either the width or height dimension is <1.5d. In this case, the plenum may not behave as an expansion chamber, thus changing its broadband TL characteristics significantly.

Table 8 Low-Frequency Characteristics of Plenum TL

Frequency	Surface Area Coefficient A_f, dB/ft² For Plenum Volume <50 ft³	>50 ft³	Wall Effect W_e, dB Added 1 in., 2.5 lb/ft³ (Fabric Facing)	2 in., 2.5 lb/ft³ (Fabric Facing)	4 in., 2.5 lb/ft³ (Perf. Facing)	8 in., 2.5 lb/ft³ (Perf. Facing)	4 in. (Tuned, No Media)	4 in., 2.5 lb/ft³ (Double Solid Metal)
50	0.14	0.03	1	1	0	1	0	0
63	0.10	0.03	1	2	3	7	1	3
80	0.11	0.03	2	2	3	9	2	7
100	0.23	0.03	2	2	4	12	1	6
125	0.24	0.04	2	3	6	12	1	4
160	0.20	0.04	3	4	11	11	0	2
200	0.10	0.03	4	10	16	15	4	3
250	0.22	0.04	5	9	13	12	1	1
315	0.07	0.03	6	12	14	14	5	2
400	0.07	0.02	8	13	13	14	7	1
500	0.11	0.02	9	13	12	13	8	0

Source: Mouratidis and Becker (2004).

Table 9 Offset Angle Effects on TL for End-Outlet Plenum

Offset Angle Effects on TL ≤ f_c

Frequency, Hz	Offset Angle θ 0	15.0	22.5	30.0	37.5	45.0
50	0	0	0	0	0	0
63	0	0	0	0	0	0
80	0	0	−1	−3	−4	−6
100	0	1	0	−2	−3	−6
125	0	1	0	−2	−4	−6
160	0	0	−1	−2	−3	−4
200	0	0	−1	−2	−3	−5
250	0	1	2	3	5	7
315	0	4	6	8	10	14
400	0	2	4	6	9	13
500	0	1	3	6	10	15
≥630	N/A	N/A	N/A	N/A	N/A	N/A

Offset Angle Effects on TL > f_c

Frequency, Hz	Offset Angle θ 0	15.0	22.5	30.0	37.5	45.0
≤160	N/A	N/A	N/A	N/A	N/A	N/A
200	0	1	4	9	14	20
250	0	2	4	8	13	19
315	0	1	2	3	4	5
400	0	1	2	3	4	6
500	0	0	1	2	4	5
630	0	1	2	3	5	7
800	0	1	2	2	3	3
1000	0	1	2	4	6	9
1250	0	0	2	4	6	9
1600	0	0	1	1	2	3
2000	0	1	2	4	7	10
2500	0	1	2	3	5	8
3150	0	0	2	4	6	9
4000	0	0	2	5	8	12
5000	0	0	3	6	10	15

N/A = Not applicable

Table 10 Elbow Effect, dB

Frequency, Hz	>f_c	≤f_c
50	≤160 N/A	2
63		3
80		6
100		5
125		3
160		0
200	3	−2
250	6	−3
315	3	−1
400	3	0
500	2	0
630	3	≥630 N/A
800	3	
1000	2	
1250	2	
1600	2	
2000	2	
2500	2	
3150	2	
4000	2	
5000	1	

N/A = Not applicable

Example 2. A small plenum with acoustically lined surfaces is 5.9 ft high, 4.0 ft wide, and 5.9 ft long. The inlet and outlet are each 3.0 ft wide by 2.0 ft high. The horizontal offset between centers of the plenum inlet and outlet is 1.0 ft. The vertical offset is 4.0 ft. The inside of the plenum is completely lined with 1 in. thick fiberglass insulation board, with sound absorption values as shown in Table 8. Determine the transmission loss TL associated with this plenum.

Solution:

The areas of the inlet section, outlet section, and overall surfaces are

$$S_{in} = 3.0 \times 2.0 = 6.0 \text{ ft}^2$$

$$S_{out} = 3.0 \times 2.0 = 6.0 \text{ ft}^2$$

S = Total surface area (all walls with lining)
   = 2(5.9 × 4.0) + 2(5.9 × 5.9) + 2(4.0 × 5.9) − 6.0 − 6.0
   = 152.0 ft²

with l = 5.9 ft, r_v = 4.0 ft, and r_h = 1.0 ft,

$$r = (5.9^2 + 4.0^2 + 1.0^2)^{1/2} = 7.2 \text{ ft}$$

$$\theta = \cos^{-1}(5.9/7.2) = 35°$$

The cutoff frequency f_c is

$$f_c = 1132/(2 \times 3.0) = 189 \text{ Hz}$$

where 1132 ft/s is the approximate speed of sound in standard air.

Frequency Range #1 (1/3-octave TL in 50 Hz ≤ f ≤ f_c range)

$$\text{TL} = A_f \times S + W_e + \text{Offset angle effect}$$

(Consult Table 7 for A_f and W_e and Table 9 for offset angle effect.)

Frequency Range #2 (1/3-octave TL in $f_c < f \le 5000$ Hz range)

$$\text{TL} = b\left[\frac{S_{out}Q}{4\pi r^2} + \frac{S_{out}(1-\alpha_a)}{S\alpha_a}\right]^n + \text{Offset angle effect}$$

where

$b = 3.505$

$n = -0.359$

$Q = 4$ (directivity factor for inlet opening close to adjacent wall or bihedral corner of plenum)

$\alpha_a = $ 1/3-octave average absorption values for 1 in. fiberglass lining (see Table 8)

offset angle effect = see Table 9

The results are tabulated as follows:

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
1/3-Octave TL in	Freq., Hz	A_f, dB/ft^2	W_e, dB	OAE, dB	TL for Frequency Range 1,[a] dB	A_{TL}, dB	TL for Frequency Range 2,[b] dB	Net TL,[c] dB
$50 \le f \le$ 189 Hz	50	0.03	1	0	6			6
	63	0.03	1	0	6			6
	80	0.03	2	−4	3			3
	100	0.03	2	−3	4			4
	125	0.04	2	−4	4			4
	160	0.04	3	−3	6			6
$f_c < f \le$ 5000 Hz	200			12		8	20	20
	250			11		8	19	19
	315			4		9	13	13
	400			4		10	14	14
	500			3		10	13	13
	630			4		10	14	14
	800			3		11	14	14
	1000			5		11	16	16
	1300			5		11	16	16
	1600			2		11	13	13
	2000			6		11	17	17
	2500			4		11	15	15
	3200			5		11	16	16
	4000			7		11	18	18
	5000			8		11	19	19

OAE = Offset Angle Effect
Notes:
[a]Column 1 × S + Column 2 + Column 3
[b]Column 3 + Column 5
[c]Column 4 + Column 6

Unlined Rectangular Sheet Metal Ducts. Straight, unlined rectangular sheet metal ducts provide a fairly significant amount of low-frequency sound attenuation. Table 11 shows the results of selected unlined rectangular sheet metal ducts (Cummings 1983; Reynolds and Bledsoe 1989a; Ver 1978; Woods Fan Division 1973). Attenuation values in Table 11 apply only to rectangular sheet metal ducts with the lightest gages allowed by Sheet Metal and Air Conditioning Contractors' National Association, Inc. (SMACNA) HVAC duct construction standards. Attenuation for lengths greater than 10 ft is not well documented.

Sound energy attenuated at low frequencies in rectangular ducts may manifest itself as breakout noise along the duct. Low-frequency breakout noise should therefore be checked. For additional information on breakout noise, see the section on Sound Radiation Through Duct Walls.

Acoustically Lined Rectangular Sheet Metal Ducts. Internal duct lining for rectangular sheet metal ducts can be used to provide both thermal insulation and sound attenuation. The thickness of duct linings for thermal insulation usually varies from 0.5 to 2 in; density of fiberglass lining usually varies between 1.5 and 3.0 lb/ft^3, but may be as low as 0.75 lb/ft^3. For fiberglass duct lining to attenuate fan sound effectively, it should have a minimum thickness of 1 in. Tables 12 and 13 give attenuation values of selected rectangular sheet metal

Table 11   Sound Attenuation in Unlined Rectangular Sheet Metal Ducts

		Attenuation, dB/ft Octave Midband Frequency, Hz			
Duct Size, in.	P/A, 1/ft	63	125	250	>250
6 × 6	8.0	0.30	0.20	0.10	0.10
12 × 12	4.0	0.35	0.20	0.10	0.06
12 × 24	3.0	0.40	0.20	0.10	0.05
24 × 24	2.0	0.25	0.20	0.10	0.03
48 × 48	1.0	0.15	0.10	0.07	0.02
72 × 72	0.7	0.10	0.10	0.05	0.02

Table 12   Insertion Loss for Rectangular Sheet Metal Ducts with 1 in. Fiberglass Lining

	Insertion Loss, dB/ft Octave Midband Frequency, Hz					
Dimensions, in.	125	250	500	1000	2000	4000
6 × 6	0.6	1.5	2.7	5.8	7.4	4.3
6 × 10	0.5	1.2	2.4	5.1	6.1	3.7
6 × 12	0.5	1.2	2.3	5.0	5.8	3.6
6 × 18	0.5	1.0	2.2	4.7	5.2	3.3
8 × 8	0.5	1.2	2.3	5.0	5.8	3.6
8 × 12	0.4	1.0	2.1	4.5	4.9	3.2
8 × 16	0.4	0.9	2.0	4.3	4.5	3.0
8 × 24	0.4	0.8	1.9	4.0	4.1	2.8
10 × 10	0.4	1.0	2.1	4.4	4.7	3.1
10 × 16	0.4	0.8	1.9	4.0	4.0	2.7
10 × 20	0.3	0.8	1.8	3.8	3.7	2.6
10 × 30	0.3	0.7	1.7	3.6	3.3	2.4
12 × 12	0.4	0.8	1.9	4.0	4.1	2.8
12 × 18	0.3	0.7	1.7	3.7	3.5	2.5
12 × 24	0.3	0.6	1.7	3.5	3.2	2.3
12 × 36	0.3	0.6	1.6	3.3	2.9	2.2
15 × 15	0.3	0.7	1.7	3.6	3.3	2.4
15 × 22	0.3	0.6	1.6	3.3	2.9	2.2
15 × 30	0.3	0.5	1.5	3.1	2.6	2.0
15 × 45	0.2	0.5	1.4	2.9	2.4	1.9
18 × 18	0.3	0.6	1.6	3.3	2.9	2.2
18 × 28	0.2	0.5	1.4	3.0	2.4	1.9
18 × 36	0.2	0.5	1.4	2.8	2.2	1.8
18 × 54	0.2	0.4	1.3	2.7	2.0	1.7
24 × 24	0.2	0.5	1.4	2.8	2.2	1.8
24 × 36	0.2	0.4	1.2	2.6	1.9	1.6
24 × 48	0.2	0.4	1.2	2.4	1.7	1.5
24 × 72	0.2	0.3	1.1	2.3	1.6	1.4
30 × 30	0.2	0.4	1.2	2.5	1.8	1.6
30 × 45	0.2	0.3	1.1	2.3	1.6	1.4
30 × 60	0.2	0.3	1.1	2.2	1.4	1.3
30 × 90	0.1	0.3	1.0	2.1	1.3	1.2
36 × 36	0.2	0.3	1.1	2.3	1.6	1.4
36 × 54	0.1	0.3	1.0	2.1	1.3	1.2
36 × 72	0.1	0.3	1.0	2.0	1.2	1.2
36 × 108	0.1	0.2	0.9	1.9	1.1	1.1
42 × 42	0.2	0.3	1.0	2.1	1.4	1.3
42 × 64	0.1	0.3	0.9	1.9	1.2	1.1
42 × 84	0.1	0.2	0.9	1.8	1.1	1.1
42 × 126	0.1	0.2	0.9	1.7	1.0	1.0
48 × 48	0.1	0.3	1.0	2.0	1.2	1.2
48 × 72	0.1	0.2	0.9	1.8	1.0	1.0
48 × 96	0.1	0.2	0.8	1.7	1.0	1.0
48 × 144	0.1	0.2	0.8	1.6	0.9	0.9

ducts for 1 and 2 in. duct lining, respectively (Kuntz 1986; Kuntz and Hoover 1987; Machen and Haines 1983; Reynolds and Bledsoe 1989a). Note that attenuation values shown in these tables are based on laboratory tests using 10 ft lengths of duct; for designs incorporating other distances, actual values will be different. The total attenuated noise will never be below the generated noise level in the duct.

Table 13 Insertion Loss for Rectangular Sheet Metal Ducts with 2 in. Fiberglass Lining

Dimensions, in.	Insertion Loss, dB/ft Octave Midband Frequency, Hz					
	125	250	500	1000	2000	4000
6 × 6	0.8	2.9	4.9	7.2	7.4	4.3
6 × 10	0.7	2.4	4.4	6.4	6.1	3.7
6 × 12	0.6	2.3	4.2	6.2	5.8	3.6
6 × 18	0.6	2.1	4.0	5.8	5.2	3.3
8 × 8	0.6	2.3	4.2	6.2	5.8	3.6
8 × 12	0.6	1.9	3.9	5.6	4.9	3.2
8 × 16	0.5	1.8	3.7	5.4	4.5	3.0
8 × 24	0.5	1.6	3.5	5.0	4.1	2.8
10 × 10	0.6	1.9	3.8	5.5	4.7	3.1
10 × 16	0.5	1.6	3.4	5.0	4.0	2.7
10 × 20	0.4	1.5	3.3	4.8	3.7	2.6
10 × 30	0.4	1.3	3.1	4.5	3.3	2.4
12 × 12	0.5	1.6	3.5	5.0	4.1	2.8
12 × 18	0.4	1.4	3.2	4.6	3.5	2.5
12 × 24	0.4	1.3	3.0	4.3	3.2	2.3
12 × 36	0.4	1.2	2.9	4.1	2.9	2.2
15 × 15	0.4	1.3	3.1	4.5	3.3	2.4
15 × 22	0.4	1.2	2.9	4.1	2.9	2.2
15 × 30	0.3	1.1	2.7	3.9	2.6	2.0
15 × 45	0.3	1.0	2.6	3.6	2.4	1.9
18 × 18	0.4	1.2	2.9	4.1	2.9	2.2
18 × 28	0.3	1.0	2.6	3.7	2.4	1.9
18 × 36	0.3	0.9	2.5	3.5	2.2	1.8
18 × 54	0.3	0.8	2.3	3.3	2.0	1.7
24 × 24	0.3	0.9	2.5	3.5	2.2	1.8
24 × 36	0.3	0.8	2.3	3.2	1.9	1.6
24 × 48	0.2	0.7	2.2	3.0	1.7	1.5
24 × 72	0.2	0.7	2.0	2.9	1.6	1.4
30 × 30	0.2	0.8	2.2	3.1	1.8	1.6
30 × 45	0.2	0.7	2.0	2.9	1.6	1.4
30 × 60	0.2	0.6	1.9	2.7	1.4	1.3
30 × 90	0.2	0.5	1.8	2.6	1.3	1.2
36 × 36	0.2	0.7	2.0	2.9	1.6	1.4
36 × 54	0.2	0.6	1.9	2.6	1.3	1.2
36 × 72	0.2	0.5	1.8	2.5	1.2	1.2
36 × 108	0.2	0.5	1.7	2.3	1.1	1.1
42 × 42	0.2	0.6	1.9	2.6	1.4	1.3
42 × 64	0.2	0.5	1.7	2.4	1.2	1.1
42 × 84	0.2	0.5	1.6	2.3	1.1	1.1
42 × 126	0.1	0.4	1.6	2.2	1.0	1.0
48 × 48	0.2	0.5	1.8	2.5	1.2	1.2
48 × 72	0.2	0.4	1.6	2.3	1.0	1.0
48 × 96	0.1	0.4	1.5	2.1	1.0	1.0
48 × 144	0.1	0.4	1.5	2.0	0.9	0.9

Table 14 Sound Attenuation in Unlined Straight Round Ducts

Diameter, in.	Attenuation, dB/ft Octave Midband Frequency, Hz						
	63	125	250	500	1000	2000	4000
D = 7	0.03	0.03	0.05	0.05	0.10	0.10	0.10
7 < D = 15	0.03	0.03	0.03	0.05	0.07	0.07	0.07
15 < D = 30	0.02	0.02	0.02	0.03	0.05	0.05	0.05
30 < D = 60	0.01	0.01	0.01	0.02	0.02	0.02	0.02

SQUARE ELBOW   RADIUSED ELBOW
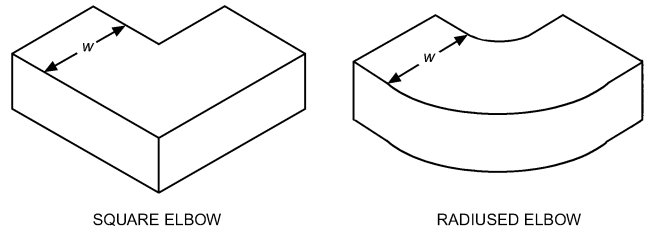
Fig. 17 Rectangular Duct Elbows

Table 14 lists sound attenuation values for unlined round ducts (Kuntz and Hoover 1987; Woods Fan Division 1973).

Acoustically Lined Round Sheet Metal Ducts. The literature provides very little data on insertion loss for acoustically lined round ducts; usually only manufacturers' product data are available. Tables 15 and 16 give insertion loss values for dual-wall round sheet metal ducts with 1 and 2 in. acoustical lining, respectively (Reynolds and Bledsoe 1989b). The acoustical lining is a 0.75 lb/ft^3 density fiberglass blanket, which is covered by an internal liner of perforated galvanized sheet metal with an open area of 25%. The data in Tables 15 and 16 were collected from 20 ft duct sections. Because there are many options available for round ducts, attenuation may significantly vary from the data provided in the tables.

Rectangular Sheet Metal Duct Elbows. Table 17 displays insertion loss values for unlined and lined square elbows without turning vanes (Beranek 1960). For lined square elbows, duct lining must extend at least two duct widths *w* beyond the elbow. Table 17 applies only where the duct is lined before and after the elbow. Table 18 gives insertion loss values for unlined radiused elbows. Table 19 gives insertion loss values for unlined and lined square elbows with turning vanes. The quantity *fw* in Tables 17 to 19 is the midfrequency of the octave band times the width of the elbow (Figure 17) (Beranek 1960; Ver 1983b).

Nonmetallic Insulated Flexible Ducts. Nonmetallic insulated flexible ducts can significantly reduce airborne noise. Insertion loss values for specified duct diameters and lengths are given in Table 20 and in Appendix D of ARI *Standard* 885. Recommended duct lengths are normally 3 to 6 ft. Take care to keep flexible ducts straight; bends should have as long a radius as possible. Although an abrupt bend may provide some additional insertion loss, the airflow-generated noise associated with airflow in the bend may be unacceptably high. Because of potentially high breakout sound levels associated with flexible ducts, care should be taken when using flexible ducts above sound-sensitive spaces.

Duct Silencers. Silencers, sometimes called sound attenuators, sound traps, or mufflers, are designed to reduce the noise transmitted from a source to a receiver. For HVAC applications, the most common silencers are duct silencers, installed on the intake and/or discharge side of a fan or air handler. Also, they may be used on the receiver side of other noise generators such as terminal boxes, valves, dampers, etc.

Duct silencers are available in varying shapes and sizes to fit project ductwork. Generally, a duct silencer's outer appearance is similar to a piece of ductwork. It consists of a sheet metal casing

Insertion loss values in Tables 12 and 13 are the difference in the sound pressure level measured in a reverberation room with sound propagating through an unlined section of rectangular duct minus the corresponding sound pressure level measured when the unlined section of rectangular duct is replaced with a similar section of acoustically lined rectangular duct. The net result is the attenuation resulting from adding duct liner to a sheet metal duct.

Insertion loss and attenuation values discussed in this section apply only to rectangular sheet metal ducts made with the lightest gages allowed by SMACNA HVAC duct construction standards. Attenuation for lengths greater than 10 ft is not well documented.

Unlined Round Sheet Metal Ducts. As with unlined rectangular ducts, unlined round ducts provide some natural sound attenuation that should be taken into account when designing a duct system. Compared to rectangular ducts, round ducts are much more rigid and thus do not absorb as much sound energy. Because of this, round ducts only provide about one-tenth the sound attenuation at low frequencies as rectangular ducts. However, breakout from round ducts is significantly less than that from other shapes.

Table 15 Insertion Loss for Acoustically Lined Round Ducts with 1 in. Lining

Diameter, in.	Insertion Loss, dB/ft Octave Midband Frequency, Hz							
	63	125	250	500	1000	2000	4000	8000
6	0.38	0.59	0.93	1.53	2.17	2.31	2.04	1.26
8	0.32	0.54	0.89	1.50	2.19	2.17	1.83	1.18
10	0.27	0.50	0.85	1.48	2.20	2.04	1.64	1.12
12	0.23	0.46	0.81	1.45	2.18	1.91	1.48	1.05
14	0.19	0.42	0.77	1.43	2.14	1.79	1.34	1.00
16	0.16	0.38	0.73	1.40	2.08	1.67	1.21	0.95
18	0.13	0.35	0.69	1.37	2.01	1.56	1.10	0.90
20	0.11	0.31	0.65	1.34	1.92	1.45	1.00	0.87
22	0.08	0.28	0.61	1.31	1.82	1.34	0.92	0.83
24	0.07	0.25	0.57	1.28	1.71	1.24	0.85	0.80
26	0.05	0.22	0.53	1.24	1.59	1.14	0.79	0.77
28	0.03	0.19	0.49	1.20	1.46	1.04	0.74	0.74
30	0.02	0.16	0.45	1.16	1.33	0.95	0.69	0.71
32	0.01	0.14	0.42	1.12	1.20	0.87	0.66	0.69
34	0	0.11	0.38	1.07	1.07	0.79	0.63	0.66
36	0	0.08	0.35	1.02	0.93	0.71	0.60	0.64
38	0	0.06	0.31	0.96	0.80	0.64	0.58	0.61
40	0	0.03	0.28	0.91	0.68	0.57	0.55	0.58
42	0	0.01	0.25	0.84	0.56	0.50	0.53	0.55
44	0	0	0.23	0.78	0.45	0.44	0.51	0.52
46	0	0	0.20	0.71	0.35	0.39	0.48	0.48
48	0	0	0.18	0.63	0.26	0.34	0.45	0.44
50	0	0	0.15	0.55	0.19	0.29	0.41	0.40
52	0	0	0.14	0.46	0.13	0.25	0.37	0.34
54	0	0	0.12	0.37	0.09	0.22	0.31	0.29
56	0	0	0.10	0.28	0.08	0.18	0.25	0.22
58	0	0	0.09	0.17	0.08	0.16	0.18	0.15
60	0	0	0.08	0.06	0.10	0.14	0.09	0.07

Table 16 Insertion Loss for Acoustically Lined Round Ducts with 2 in. Lining

Diameter, in.	Insertion Loss, dB/ft Octave Midband Frequency, Hz							
	63	125	250	500	1000	2000	4000	8000
6	0.56	0.80	1.37	2.25	2.17	2.31	2.04	1.26
8	0.51	0.75	1.33	2.23	2.19	2.17	1.83	1.18
10	0.46	0.71	1.29	2.20	2.20	2.04	1.64	1.12
12	0.42	0.67	1.25	2.18	2.18	1.91	1.48	1.05
14	0.38	0.63	1.21	2.15	2.14	1.79	1.34	1.00
16	0.35	0.59	1.17	2.12	2.08	1.67	1.21	0.95
18	0.32	0.56	1.13	2.10	2.01	1.56	1.10	0.90
20	0.29	0.52	1.09	2.07	1.92	1.45	1.00	0.87
22	0.27	0.49	1.05	2.03	1.82	1.34	0.92	0.83
24	0.25	0.46	1.01	2.00	1.71	1.24	0.85	0.80
26	0.24	0.43	0.97	1.96	1.59	1.14	0.79	0.77
28	0.22	0.40	0.93	1.93	1.46	1.04	0.74	0.74
30	0.21	0.37	0.90	1.88	1.33	0.95	0.69	0.71
32	0.20	0.34	0.86	1.84	1.20	0.87	0.66	0.69
34	0.19	0.32	0.82	1.79	1.07	0.79	0.63	0.66
36	0.18	0.29	0.79	1.74	0.93	0.71	0.60	0.64
38	0.17	0.27	0.76	1.69	0.80	0.64	0.58	0.61
40	0.16	0.24	0.73	1.63	0.68	0.57	0.55	0.58
42	0.15	0.22	0.70	1.57	0.56	0.50	0.53	0.55
44	0.13	0.20	0.67	1.50	0.45	0.44	0.51	0.52
46	0.12	0.17	0.64	1.43	0.35	0.39	0.48	0.48
48	0.11	0.15	0.62	1.36	0.26	0.34	0.45	0.44
50	0.09	0.12	0.60	1.28	0.19	0.29	0.41	0.40
52	0.07	0.10	0.58	1.19	0.13	0.25	0.37	0.34
54	0.05	0.08	0.56	1.10	0.09	0.22	0.31	0.29
56	0.02	0.05	0.55	1.00	0.08	0.18	0.25	0.22
58	0	0.03	0.53	0.90	0.08	0.16	0.18	0.15
60	0	0	0.53	0.79	0.10	0.14	0.09	0.07

Table 17 Insertion Loss of Unlined and Lined Square Elbows Without Turning Vanes

	Insertion Loss, dB	
	Unlined Elbows	Lined Elbows
$fw < 1.9$	0	0
$1.9 \le fw < 3.8$	1	1
$3.8 \le fw < 7.5$	5	6
$7.5 \le fw < 15$	8	11
$15 \le fw < 30$	4	10
$fw > 30$	3	10

Note: f = center frequency, kHz, and w = width, in.

Table 18 Insertion Loss of Round Elbows

	Insertion Loss, dB
$fw < 1.9$	0
$1.9 \le fw < 3.8$	1
$3.8 \le fw < 7.5$	2
$fw > 7.5$	3

Note: f = center frequency, kHz, and w = width, in.

Table 19 Insertion Loss of Unlined and Lined Square Elbows with Turning Vanes

	Insertion Loss, dB	
	Unlined Elbows	Lined Elbows
$fw < 1.9$	0	0
$1.9 \le fw < 3.8$	1	1
$3.8 \le fw < 7.5$	4	4
$7.5 \le fw < 15$	6	7
$fw > 15$	4	7

Note: f = center frequency, kHz, and w = width, in.
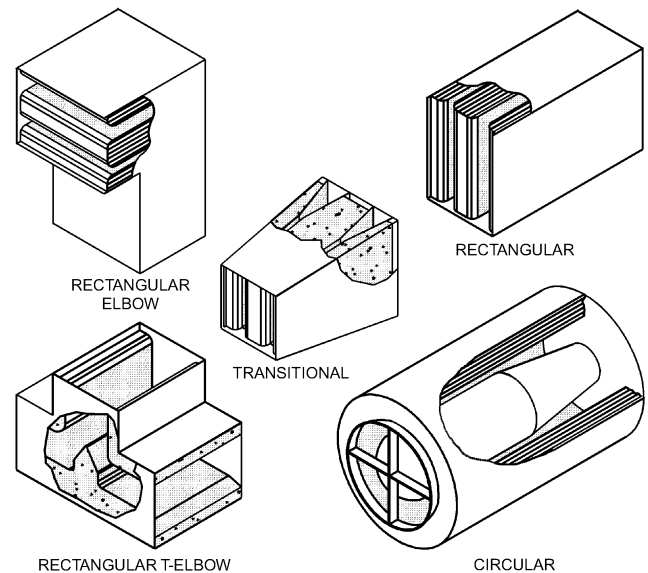
Fig. 18 Duct Silencer Configurations

with length commonly ranging from 3 to 10 ft. Common shapes include rectangular, round, elbow, tee, and transitional. Figure 18 shows some duct silencer configurations.

All silencers can be rated for (1) insertion loss, (2) dynamic insertion loss, (3) pressure drop, and (4) generated noise.

Insertion loss is the reduction in the sound power level at the receiver after the silencer is installed ("inserted") in the system. Insertion loss is measured as a function of frequency and commonly published in full octave bands ranging from 63 to 8000 Hz.

Table 20   Lined Flexible Duct Insertion Loss

Diameter, in.	Length, ft	Insertion Loss, dB Octave Midband Frequency, Hz						
		63	125	250	500	1000	2000	4000
4	12	6	11	12	31	37	42	27
	9	5	8	9	23	28	32	20
	6	3	6	6	16	19	21	14
	3	2	3	3	8	9	11	7
5	12	7	12	14	32	38	41	26
	9	5	9	11	24	29	31	20
	6	4	6	7	16	19	21	13
	3	2	3	4	8	10	10	7
6	12	8	12	17	33	38	40	26
	9	6	9	13	25	29	30	20
	6	4	6	9	17	19	20	13
	3	2	3	4	8	10	10	7
7	12	9	12	19	33	37	38	25
	9	6	9	14	25	28	29	19
	6	4	6	10	17	19	19	13
	3	2	3	5	8	9	10	6
8	12	8	11	21	33	37	37	24
	9	6	8	16	25	28	28	18
	6	4	6	11	17	19	19	12
	3	2	3	5	8	9	9	6
9	12	8	11	22	33	37	36	22
	9	6	8	17	25	28	27	17
	6	4	6	11	17	19	18	11
	3	2	3	6	8	9	9	6
10	12	8	10	22	32	36	34	21
	9	6	8	17	24	27	26	16
	6	4	5	11	16	18	17	11
	3	2	3	6	8	9	9	5
12	12	7	9	20	30	34	31	18
	9	5	7	15	23	26	23	14
	6	3	5	10	15	17	16	9
	3	2	2	5	8	9	8	5
14	12	5	7	16	27	31	27	14
	9	4	5	12	20	23	20	11
	6	3	4	8	14	16	14	7
	3	1	2	4	7	8	7	4
16	12	2	4	9	23	28	23	9
	9	2	3	7	17	21	17	7
	6	1	2	5	12	14	12	5
	3	1	1	2	6	7	6	2

Note: 63 Hz insertion loss values estimated from higher-frequency insertion loss values.

Dynamic insertion loss is insertion loss with given airflow direction and velocity. A silencer's insertion loss varies depending on whether sound is traveling in the same or opposite direction as airflow. Silencer performance changes with absolute duct velocity. However, airflow velocity generally does not significantly affect silencers giving a pressure drop of 0.35 in. of water or less, including system effects.

Pressure drop is measured across the silencer at a given velocity. Good flow conditions are required at both the inlet and discharge of the silencer. The measuring points are usually 2.5 to 5 duct diameters upstream and downstream of the silencer to avoid turbulent flow areas near the silencer and to allow for any static pressure regain.

Airflow-generated noise is the sound power generated by the silencer when quiet air flows through it. This represents the **noise floor**, or the lowest level achievable regardless of high insertion loss values. A silencer's generated noise is a function of frequency and is referenced to specific velocities and airflow direction (forward or reverse). The airflow-generated sound power of the silencer is logarithmically proportional to silencer cross-sectional area.
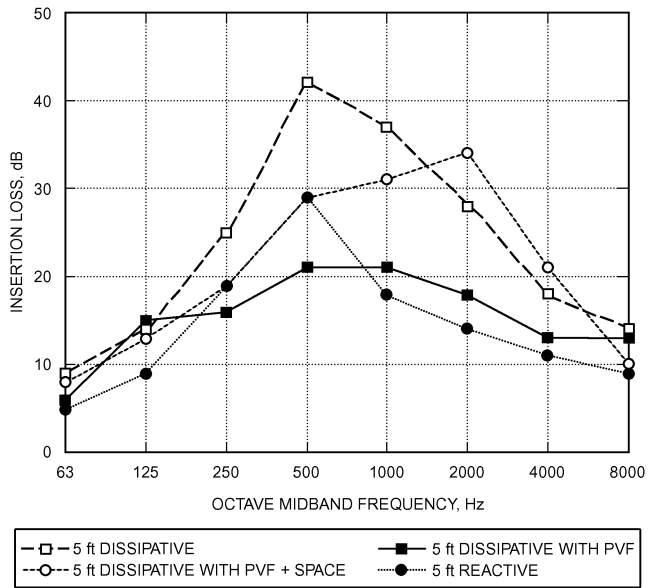
Fig. 19   Comparison of 5 ft Long Dissipative and Reactive Silencer Performance

There are three types of HVAC duct silencers: dissipative (with acoustic media), reactive (no media), and active.

Dissipative Silencers. Dissipative silencers use sound-absorptive media such as fiberglass as the primary means of attenuating sound; mineral wool can be used in high-temperature applications but may contain too much contamination ("shot") for commercial HVAC applications. Usually, the absorptive medium is covered by perforated metal to protect it from erosion by airflow. If internal silencer velocities are high (faster than 4500 fpm), media erosion may be further reduced by a layer of material such as fiberglass cloth or film liner placed between the absorptive media and the perforated metal [note that film liner has not been rated according to National Fire Protection Association (NFPA) standards]. The thicker and more rigid the protective material, the more it will degrade the insertion loss performance of the silencer. Special methods of applying the material may be used to reduce, but not eliminate, the degradation. Consult manufacturers for construction and testing details.

Dissipative silencer performance is primarily a function of silencer length; airflow constriction; number, thickness, and shape of splitters or centerbodies; and type and density of absorptive media. The absorptive media allows dissipative silencers to provide significant insertion loss performance over a wide frequency range.

Insertion loss performance does not necessarily increase linearly with silencer length; for a given length, silencer designs can produce varying insertion loss and pressure drop data. Even at the same pressure drop and length, silencers can be configured to provide varying insertion loss performance across the frequency spectrum.

Reactive Silencers. Reactive silencers are constructed only of metal, both solid and perforated, with chambers of specially designed shapes and sizes behind the perforated metal that are tuned as resonators to react with and reduce sound power at certain frequencies. The outward appearance of reactive silencers is similar to that of their dissipative counterparts. However, because of tuning, insertion loss over a wide frequency range is more difficult to achieve. Longer lengths may be required to achieve similar insertion loss performance as dissipative silencers. Airflow generally increases the insertion loss of reactive silencers.

Figure 19 compares insertion loss of dissipative silencers, with and without protective polyvinyl fluoride (PVF) materials, against that of a reactive silencer for the same pressure drop.

Active Silencers. Active duct silencers, sometimes called noise canceling systems, produce inverse sound waves that cancel noise primarily at low frequencies. An input microphone measures noise in the duct and converts it to electrical signals, which are processed digitally to generate opposite, "mirror-image" sound signals of equal amplitude. A secondary noise source destructively interferes with the primary noise and cancels a significant portion of it. An error microphone measures residual sound beyond the silencer and provides feedback to adjust the computer model for improved performance.

Because components are mounted outside the airflow, there is no pressure loss or airflow-generated noise. Performance is limited, however, if excessive turbulence is detected by the microphones. Manufacturers recommend using active silencers where duct velocities are less than 1500 fpm and where duct configurations are conducive to smooth, evenly distributed airflow. If noise levels increase, an active silencer then increases the insertion loss to compensate for the increased source noise.

Active silencers have significant low-frequency insertion loss but little mid- and high-frequency insertion loss. If required, combinations of active (for low-frequency components) and passive (for mid- and high-frequency components) can be used to achieve insertion loss over a wide frequency range.

Test Standard. Data for dissipative and reactive silencers should be obtained from tests consistent with the procedures outlined in ASTM *Standard* E477. (This standard has not been verified for determining performance of active silencers.) Because insertion loss measurements use a substitution technique, reasonable (± 3 dB) insertion loss values can be achieved down to 63 Hz. Airflow-generated noise, however, cannot be measured accurately below 100 Hz because of the lack of a standardized means of qualifying the reverberant rooms for sound power measurements at lower frequencies (a function of room size). Round-robin tests performed at several manufacturers' and independent testing laboratories showed that airflow-generated sound power data has an expected standard deviation of ± 3 to 6 dB over the octave band frequency range of 125 to 8000 Hz. (For normal distribution, uncertainty with a 95% confidence interval is about two standard deviations.)

Silencer Selection Issues. When selecting a duct silencer, consider the following:

- Insertion loss required to achieve required room sound criteria
- Allowable pressure drop (if no specific requirement, then keep under 0.35 in. of water, including system effects; when system effects are unknown, keep under 0.20 in. of water, excluding system effects) at system duct velocity
- Available space
- Amount of airflow-generated noise that can be tolerated

Insertion Loss Issues

To determine the insertion loss required, analyze the duct system, summing noise-generating mechanisms and subtracting attenuation elements (not including the silencer). The silencer's required insertion loss is the amount by which the estimated resultant sound pressure level in the space exceeds the room criteria for the space. The user should consider both the sound path through the ductwork and outlets as well as potential locations where sound may break out of the ductwork.

Pressure Drop Issues

Care should be taken in applying test data to actual project installations. Adverse aerodynamic system effects can significantly affect silencer performance. That is, if the silencer is located where less-than-ideal conditions exists on the inlet and/or the discharge of the silencer (3 to 5 duct diameters of straight duct), then the silencer's effective pressure drop (PD) is increased (total silencer PD = silencer PD per ASTM E477 + system effect losses). In some situations, the added system effect losses can be greater than the silencer's pressure drop. Some manufacturers give guidelines for

Table 21 Approximate Silencer System Effect Factors

Silencer Condition	Pressure Drop Factor*
Inlet (within 3 to 4 duct diameters)	
Straight unobstructed duct	1.0
Free air/plenum with smooth inlet	1.05
Radius elbow, with turning vanes	1.05
no turning vanes	1.1
Miter elbow	1.3
Free air/plenum with sharp inlet	1.1 to 1.30
Fan	1.1 to 1.3
Outlet (within 3 to 4 duct diameters)	
Straight unobstructed duct	1.0
Duct doubles area abruptly	1.4
Radius elbow, with turning vanes	1.5
no turning vanes	1.9
Miter elbow	2.0
Abrupt expansion/plenum	2.0
Fan	1.2 to 1.4

*Silencer pressure drop (including system effects) = silencer pressure drop per test code × pressure drop factor (inlet) × pressure drop factor (outlet).

discharge configurations (Table 21); these should be considered as general guidelines. Substantial variations can occur depending on the type of silencer, its internal geometry, size of silencer, size of duct, airflow turbulence, etc. For example, an elbow fitting located immediately after a silencer prevents regain of the silencer's leaving velocity pressure. In addition, local velocities in the elbow fitting are greater than the average duct velocity that produces higher overall static pressure losses.

Silencer Location

Silencers should generally be located as close to the noise source as possible but far enough away to allow a uniform flow profile to develop. This helps contain noise at the source and limits potential points where unsilenced noise may break out. However, because turbulent airflow usually exists close to noise sources such as fans, valves, dampers, etc., the user should carefully evaluate aerodynamic system effects.

A straight silencer has a lower first cost than a transitional or elbow silencer. If space limitations prohibit effective use of a straight silencer, or if pressure drop (including system effects) is greater than the loss allowed, use of elbow or transitional silencers should be evaluated. Special fan inlet and discharge silencers, including cone and inlet box silencers, minimize aerodynamic system effects, and contain noise at the source.

Airflow-Generated Noise Issues

In most installations, airflow-generated noise is much less than, and does not contribute to, the reduced noise level on the quiet side of the silencer. This is especially true if the silencer is properly located close to the source. In general, airflow-generated noise should be evaluated if pressure drops exceed 0.35 in. of water (including system effects), the noise criterion is below RC 35, or if the silencer is located very close to or in the occupied space.

To evaluate airflow-generated noise, sum the noise-generating mechanisms (from noise source to silencer) and subtract the attenuation elements (including silencer) in the order they occur to determine the resultant sound power level on the quiet side of the silencer. This resultant level must be summed logarithmically with the silencer's generated noise (referenced to actual duct velocities, inlet and discharge configurations, and cross-sectional area). If the generated noise is more than 10 dB below the residual sound, then the silencer's generated noise will have no effect on system noise levels.

Duct Branch Sound Power Division. When sound traveling in a duct encounters a junction, the sound power contained in the incident sound waves in the main feeder duct is distributed between the

Table 22   Duct Branch Sound Power Division

$S_{Bi}/\Sigma S_{Bi}$	ΔL_{Bi}	$S_{Bi}/\Sigma S_{Bi}$	ΔL_{Bi}
1.00	0	0.10	10
0.80	1	0.08	11
0.63	2	0.063	12
0.50	3	0.050	13
0.40	4	0.040	14
0.32	5	0.032	15
0.25	6	0.025	16
0.20	7	0.020	17
0.16	8	0.016	18
0.12	9	0.012	19

Table 23   Duct End Reflection Loss: Duct Terminated in Free Space

Duct Diameter, in.	End Reflection Loss, dB Octave Midband Frequency, Hz					
	63	125	250	500	1000	2000
6	20	14	9	5	2	1
8	18	12	7	3	1	0
10	16	11	6	2	1	0
12	14	9	5	2	1	0
16	12	7	3	1	0	0
20	10	6	2	1	0	0
24	9	5	2	1	0	0
28	8	4	1	0	0	0
32	7	3	1	0	0	0
36	6	3	1	0	0	0
48	5	2	1	0	0	0
72	3	1	0	0	0	0

Table 24   Duct End Reflection Loss: Duct Terminated Flush with Wall

Duct Diameter, in.	End Reflection Loss, dB Octave Midband Frequency, Hz				
	63	125	250	500	1000
6	18	13	8	4	1
8	16	11	6	2	1
10	14	9	5	2	1
12	13	8	4	1	0
16	10	6	2	1	0
20	9	5	2	1	0
24	8	4	1	0	0
28	7	3	1	0	0
32	6	2	1	0	0
36	5	2	1	0	0
48	4	1	0	0	0
72	2	1	0	0	0

branches associated with the junction (Ver 1982, 1983b). This division of sound power is called branch sound power division. The corresponding attenuation of sound power transmitted down each branch of the junction is comprised of two components. The first is associated with reflection of the incident sound wave if the sum of the cross-sectional areas of individual branches ΣS_{Bi} differs from the cross-sectional area of the main feeder duct. The second and more dominant component is associated with energy division according to the ratio of the cross-sectional area of an individual branch S_{Bi} divided by ΣS_{Bi}. Values for the attenuation of sound power ΔL_{Bi} are given in Table 22.

Duct End Reflection Loss. When low-frequency plane sound waves interact with an opening that discharges into a large room, a significant amount of the sound energy incident on this interface is reflected back into the duct. The sound attenuation values ΔL associated with duct end reflection losses for a duct that terminates in free space are given in Table 23.

Table 24 lists values for ducts that terminate flush with a wall (AMCA *Standard* 300; Sandbakken et al. 1981). Diffusers that terminate in a suspended lay-in acoustic ceiling can be treated as terminating in free space. To use Table 23 or 24 for a duct terminating into a rectangular diffuser, calculate duct diameter D by

$$D = \sqrt{4A/\pi} \tag{8}$$

where A = area (in^2) of the rectangular duct.

Some limitations are associated with Tables 23 and 24. The tests on which these tables are based were conducted with straight sections of round ducts. These ducts directly terminated into a reverberation chamber with no restriction on the end of the duct or with a round orifice placed over the end of the duct. There was no airflow. Diffusers, round or rectangular, usually have a restriction associated with them: a damper, airflow guide vanes, a perforated metal facing, or a combination of these elements. Currently, there

are no data on the effects of these elements. It is not known whether these elements react similarly to the orifices used in tests. As a result, the effects of an orifice placed over the end of a duct are not included in these tables. Using Equation (8) to calculate D should yield reasonable results for diffusers with low aspect ratios (length/width). However, many types of diffusers (particularly slot diffusers) have high aspect ratios. It is not known whether Tables 23 and 24 can be accurately used with these diffusers.

Finally, many diffusers do not have long straight sections (greater than three duct diameters) before they terminate into a room. Many duct sections between a main feed branch and a diffuser may be curved or short. The effects of these configurations on duct end reflection loss are not known. Tables 23 and 24 can be used with reasonable accuracy for many diffuser configurations. However, caution should be used when a diffuser configuration differs from the test conditions used to derive these tables.

SOUND RADIATION THROUGH DUCT WALLS

Airflow-Generated Duct Rumble

Duct rumble is low-frequency sound generated by vibration of a flat duct surface. The vibration is caused when an HVAC fan and its connected ductwork act as a semiclosed, compressible-fluid pumping system; both acoustic and aerodynamic air pressure fluctuations at the fan are transmitted to other locations in the duct system. Rumbling occurs at the duct's resonance frequencies (Ebbing et al. 1978), and duct rumble levels of 65 to 95 dB in the 16 to 100 Hz frequency range have been measured in occupied spaces. With belt-driven fans, the rumble sound level fluctuates above and below the mean dB level by 5 to 25 dB at a rate of 2 to 10 "beats" per second (Blazier 1993). The most common beat frequency occurs at the difference between the fan rpm and twice the belt frequency (belt rpm = fan sheave diameter × sheave rpm × π/belt length). As shown in Figure 20, duct rumble is dependent on the level of duct vibration. The very low resonant frequencies at which duct rumble occurs means that the sound wavelengths are very long (10 to 70 ft), and the rumble can exert sound energy over long distances. Lightweight architectural structures such as metal frame and drywall systems near a source of duct rumble can easily vibrate and rattle in sympathy to the rumble.

Case histories indicate that duct vibration is much more prevalent when there is a dramatic change in airflow direction near the fan, and at large, flat, unreinforced duct surfaces (usually greater than 48 in. in any dimension) near the fan. Problems can occur with dimensions as small as 18 in. if high noise levels are present. Figure 21 shows duct configurations near a centrifugal fan. Good to optimum designs of fan discharge transitions minimize potential for duct rumble; however, this may not completely eliminate the potential for duct rumble, which also depends heavily on flow turbulence at the fan wheel, duct stiffness, and duct resonant characteristics.

Duct liner, sound attenuators, and duct lagging with mass-loaded vinyl over fiberglass do not reduce duct rumble. One approach to eliminate or reduce rumble is to alter the fan or motor speed, which changes the frequency of air pressure fluctuations so that they differ from duct wall resonance frequencies. Another method is to apply rigid materials, such as duct reinforcements and drywall, directly to the duct wall to change the wall resonance frequencies (Figure 22). Noise reductions of 5 to 11 dB in the 31.5 and 63 Hz octave frequency bands are possible using this treatment.

Mass-loaded materials applied in combination with absorptive materials do not alleviate duct rumble noise unless both materials are completely decoupled from the duct by a large air separation (preferably greater than 6 in.). The mass-loaded material should have a surface density greater than 4 lb/ft². An example of this type of construction, using two layers of drywall, is shown in Figure 23. Because the treatment is decoupled from the duct wall, it provides the greatest noise reduction. Mass-loaded/absorptive material directly attached to a round duct can be an effective noise control treatment for high-frequency noise above the duct rumble frequency range of 16 to 100 Hz. In addition, the stiffness of round ductwork prevents flexure of the duct wall. Where space allows, round ductwork is an effective method to prevent duct rumble (Harold 1986). However, unless round ducts are used throughout the primary duct system, duct rumble can be still generated at a remote point where round duct is converted to rectangular or flat oval.

Round ducts can have a resonant **ring frequency**, which depends on duct material and diameter. On rare occasions, loud in-duct noise, such as blade-pass frequency noise from a centrifugal or axial fan, can excite this resonance. In these instances, a sound attenuator should be located as close to the fan as possible.

Sound Breakout and Break-In from Ducts

Breakout is sound associated with fan or airflow noise inside a duct that radiates through duct walls into the surrounding area (Figure 24). Breakout can be a problem if it is not adequately attenuated before the duct runs over an occupied space (Cummings 1983; Lilly 1987). Sound that is transmitted into a duct from the surrounding area is called **break-in** (Figure 25). The main factors affecting breakout and break-in sound transmission are the transmission loss of the duct, total exposed surface area of the duct, and presence of any acoustical duct liner.

Transmission loss (TL) is the ratio of sound power incident on a partition to the sound power transmitted through a partition. This ratio varies with acoustic frequency as well as duct shape, size, and wall thickness. Higher values of transmission loss result in less noise passing through the duct wall.

Breakout Sound Transmission from Ducts. The sound power level of sound that is transmitted through a duct wall and then radiated from the exterior surface of the duct wall is given by

$$L_{w(out)} = L_{w(in)} + 10 \log\left(\frac{S}{A}\right) - \mathrm{TL}_{out} \qquad (9)$$

where

$L_{w(out)}$ = sound power level of sound radiated from outside surface of duct walls, dB
$L_{w(in)}$ = sound power level of sound inside duct, dB
S = surface area of outside sound-radiating surface of duct, in²
A = cross-section area of inside of duct, in²
TL_{out} = normalized duct breakout transmission loss (independent of S and A), dB

Values of TL_{out} for rectangular ducts are given in Table 25, for round ducts in Table 26, and for flat oval ducts in Table 27 (Cummings 1983, 1985; Lilly 1987).

Equations for S and A for rectangular ducts are

$$S = 2 \times 12L(a + b) \qquad (10)$$

$$A = ab \qquad (11)$$

where

a = larger duct cross-section dimension, in.
b = smaller duct cross-section dimension, in.
L = length of duct sound-radiating surface, ft

Equations for S and A for round ducts are

$$S = 12L\pi d \qquad (12)$$
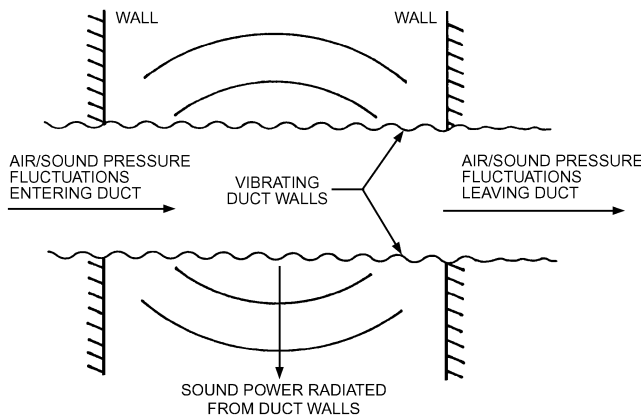
Fig. 20   Airflow-Generated Duct Rumble
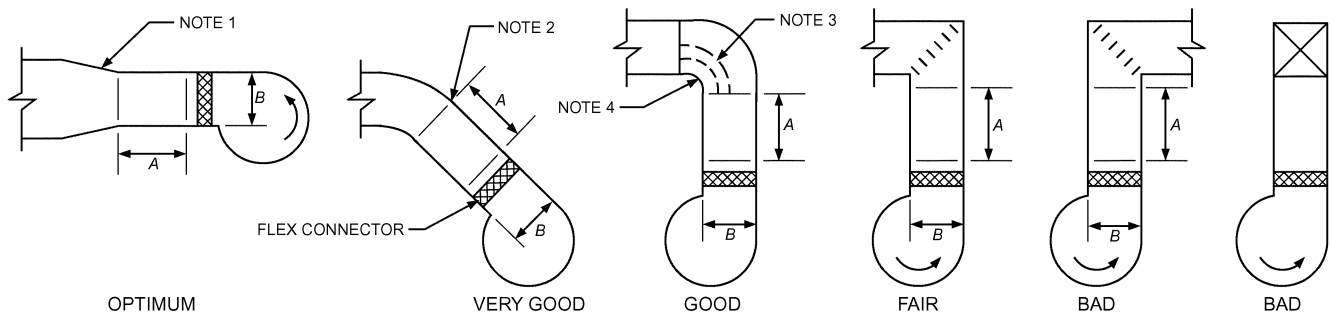
Notes:
1. Slopes of 1 in 7 preferred. Slopes of 1 in 4 permitted below 2000 fpm.
2. Dimension *A* should be at least 1.5 times *B*, where *B* is largest discharge duct dimension.
3. Rugged turning vanes should extend full radius of elbow.
4. Minimum 6 in. radius required.

Fig. 21   Various Outlet Configurations for Centrifugal Fans and Their Possible Rumble Conditions
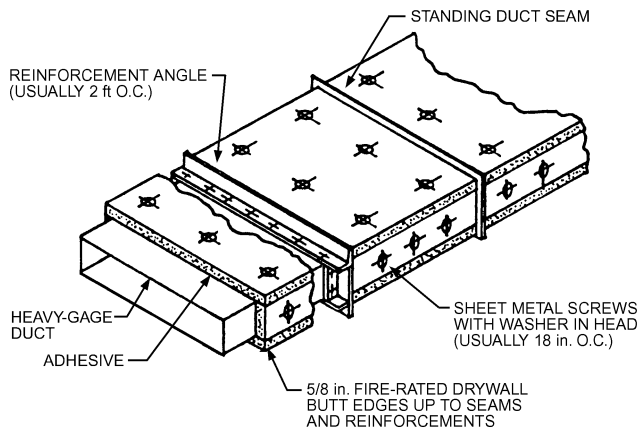
Fig. 22 Drywall Lagging for Duct Rumble
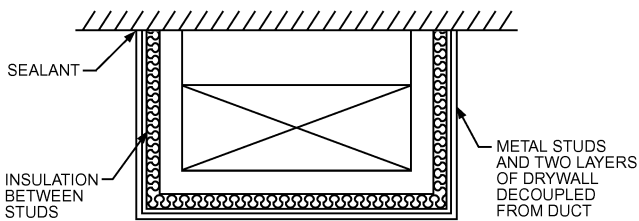
Fig. 23 Decoupled Drywall Enclosure for Duct Rumble
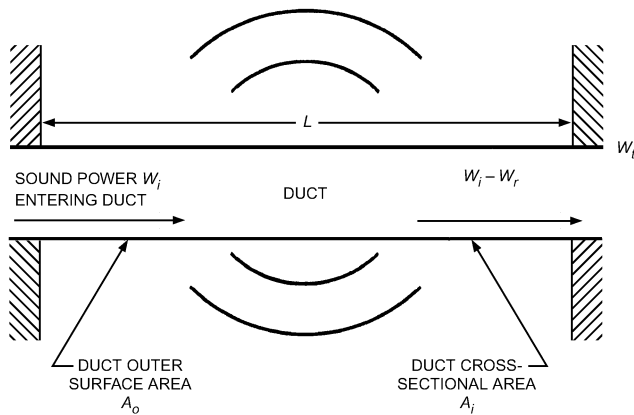
Fig. 24 Breakout Noise
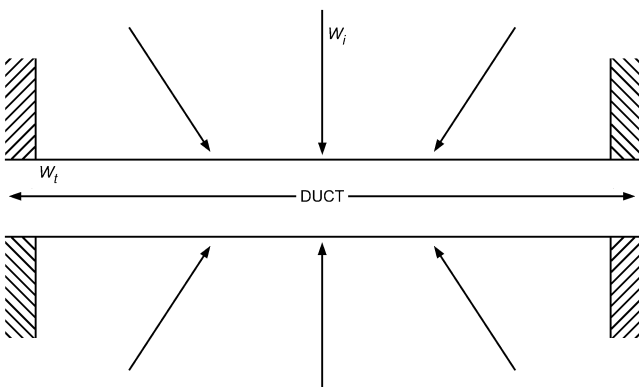
Fig. 25 Break-In Noise

Table 25 TL_{out} Versus Frequency for Rectangular Ducts

Duct Size, in.	Gage	TL_{out}, dB Octave Midband Frequency, Hz							
		63	125	250	500	1000	2000	4000	8000
12 × 12	24	21	24	27	30	33	36	41	45
12 × 24	24	19	22	25	28	31	35	41	45
12 × 48	22	19	22	25	28	31	37	43	45
24 × 24	22	20	23	26	29	32	37	43	45
24 × 48	20	20	23	26	29	31	39	45	45
48 × 48	18	21	24	27	30	35	41	45	45
48 × 96	18	19	22	25	29	35	41	45	45

Note: Data are for duct lengths of 20 ft, but values may be used for cross section shown regardless of length.

Table 26 Experimentally Measured TL_{out} Versus Frequency for Round Ducts

Diameter, in.	Length, ft	Gage	Octave Midband Frequency, Hz						
			63	125	250	500	1000	2000	4000
Long Seam Ducts									
8	15	26	>45	(53)	55	52	44	35	34
14	15	24	>50	60	54	36	34	31	25
22	15	22	>47	53	37	33	33	27	25
32	15	22	(51)	46	26	26	24	22	38
Spiral Wound Ducts									
8	10	26	>48	>64	>75	72	56	56	46
12	12	26*	52	51	53	51	50	46	36
14	10	26	>43	>53	55	33	34	35	25
24	24	24	51	53	51	44	36	26	29
	24	24*	51	51	54	44	39	33	47
26	10	24	>45	50	26	26	25	22	36
	10	16	>48	53	36	32	32	28	41
32	10	22	>43	42	28	25	26	24	40
36	24	20	51	51	52	46	36	32	55

*Ducts internally lined with 1 in. thick 1.5 pcf fiberglass with 24 ga perforated sheet metal inner liner.

Note: In cases where background sound swamped the sound radiated from duct walls, a lower limit on TL is indicated by >. Parentheses indicate measurements in which background sound has produced greater uncertainty than usual in data.

$$A = \pi \frac{d^2}{4} \tag{13}$$

where

d = duct diameter, in.
L = length of duct sound-radiating surface, ft

For flat oval ducts,

$$S = 12L[2(a - b) + \pi b] \tag{14}$$

$$A = b(a - b) + \frac{\pi b^2}{4} \tag{15}$$

where

a = length of major axis, in.
b = length of minor axis, in.
L = length of duct sound-radiating surface, ft

Equation (9) assumes no decrease in the internal sound power level with distance along the length of the duct. Thus, it is valid only for relatively short lengths of unlined duct. For long ducts or ducts that have internal acoustic lining, one approach is to divide the duct into sections, each of which is short enough to be modeled as a section of duct with constant internal sound power level over the length of each section. The recommended maximum length of each section is the length that would result in a 1 dB reduction in the internal sound power level at the frequency of interest. Alternatively, the total sound power radiated from any duct of any length (including an internally lined duct) can be calculated in a single step with a modified version of Equation (9) (Lilly 1987):

Table 27   TL$_{out}$ Versus Frequency for Flat Oval Ducts

Duct Size, in.	Gage	TL$_{out}$, dB Octave Midband Frequency, Hz						
		63	125	250	500	1000	2000	4000
12 × 6	24	31	34	37	40	43	—	—
24 × 6	24	24	27	30	33	36	—	—
24 × 12	24	28	31	34	37	—	—	—
48 × 12	22	23	26	29	32	—	—	—
48 × 24	22	27	30	33	—	—	—	—
96 × 24	20	22	25	28	—	—	—	—
96 × 48	18	28	31	—	—	—	—	—

Note: Data are for duct lengths of 20 ft, but values may be used for cross section shown regardless of length.

$$L_{w(out)} = L_{w(in)} + 10 \log\left(\frac{S^*}{A}\right) - \text{TL}_{out} \qquad (16)$$

where S^* is the effective surface area of the duct. $S^* = PL^*$, where P = duct perimeter, and L^* = effective length. The effective length L^* is calculated as

$$L^* = \frac{\gamma^L - 1}{\ln\gamma} \qquad (17)$$

where

$$\gamma = 10^{(-\alpha/10)} \qquad (18)$$

where α = duct attenuation rate, dB/ft (see Tables 11 to 16).

In most rooms where the listener is close to the duct, an estimate of the breakout sound pressure level can be obtained from

$$L_p = L_{w(out)} - 10 \log(\pi r L) + 10 \qquad (19)$$

where

L_p = sound pressure level at a specified point in the space, dB
$L_{w(out)}$ = sound power level of sound radiated from outside surface of duct walls, given by Equation (9), dB
r = distance between duct and position for which L_p is calculated, ft
L = length of the duct sound-radiating surface, ft

Example 3. A 24 in. by 24 in. by 25 ft long rectangular supply duct is constructed of 22 ga sheet metal. Given the following sound power levels in the duct, what are the breakout sound pressure levels 5 ft from the surface of the duct?

Solution: Using Equations (9) and (19),

	Octave Midband Frequency, Hz						
	63	125	250	500	1000	2000	4000
$L_{w(in)}$	90	85	80	75	70	65	60
−TL$_{out}$ (Table 25)	−20	−23	−26	−29	−32	−37	−43
10 log(S/A)	17	17	17	17	17	17	17
$L_{w(out)}$	87	79	71	63	55	45	34
−10 log($\pi r L$) + 10	−16	−16	−16	−16	−16	−16	−16
L_p, dB	71	63	55	47	39	29	18

Using Equations (16) and (19),

	Octave Midband Frequency, Hz						
	63	125	250	500	1000	2000	4000
$L_{w(in)}$	90	85	80	75	70	65	60
−TL$_{out}$ (Table 25)	−20	−23	−26	−29	−32	−37	−43
α, dB/ft (Table 11)	0.25	0.2	0.1	0.03	0.03	0.03	0.03
γ	0.94	0.95	0.98	0.99	0.99	0.99	0.99
L^*, ft	13	15	19	23	23	23	23
10 log(S^*/A)	14	15	16	17	17	17	17
$L_{w(out)}$	83	77	70	63	55	45	34
−10 log($\pi r L$) + 10	−16	−16	−16	−16	−16	−16	−16
L_p, dB	68	61	54	47	39	29	18

Example 4. Repeat Example 3, but with 2 in. thick internal duct liner.

Solution: Using Equations (9) and (19),

	Octave Midband Frequency, Hz						
	63	125	250	500	1000	2000	4000
$L_{w(in)}$	90	85	80	75	70	65	60
−TL$_{out}$ (Table 25)	−20	−23	−26	−29	−32	−37	−43
10 log(S/A)	17	17	17	17	17	17	17
$L_{w(out)}$	87	79	71	63	55	45	34
−10 log($\pi r L$) + 10	−16	−16	−16	−16	−16	−16	−16
L_p, dB	71	63	55	47	39	29	18

Using Equations (16) and (19),

	Octave Midband Frequency, Hz						
	63	125	250	500	1000	2000	4000
$L_{w(in)}$	90	85	80	75	70	65	60
−TL$_{out}$ (Table 25)	−20	−23	−26	−29	−32	−37	−43
α, dB/ft (Table 13)	0.15	0.3	0.9	2.5	3.5	2.2	1.8
γ	0.97	0.93	0.81	0.56	0.45	0.60	0.66
L^*, ft	172	12	5	2	1	2	2
10 log(S^*/A)	15	14	10	5	4	6	7
$L_{w(out)}$	85	76	64	51	42	34	24
−10 log($\pi r L$) + 10	−16	−16	−16	−16	−16	−16	−16
L_p, dB	69	60	48	35	26	18	8

Example 5. Repeat Example 4 using 24 in. diameter spiral round duct, 24 ga, 25 ft long with 1 in. thick acoustical duct lining.

Solution: Using Equations (9) and (19),

	Octave Midband Frequency, Hz						
	63	125	250	500	1000	2000	4000
$L_{w(in)}$	90	85	80	75	70	65	60
−TL$_{out}$ (Table 26)	−51	−51	−54	−44	−39	−33	−47
10 log (S/A)	17	17	17	17	17	17	17
$L_{w(out)}$	56	51	43	48	48	49	30
− 10 log($\pi r L$) + 10	−16	−16	−16	−16	−16	−16	−16
L_p, dB	40	35	27	32	32	33	14

Using Equations (16) and (19) yields

	Octave Midband Frequency, Hz						
	63	125	250	500	1000	2000	4000
$L_{w(in)}$	90	85	80	75	70	65	60
−TL$_{out}$ (Table 26)	−51	−51	−54	−44	−39	−33	−47
α, dB/ft (Table 15)	0.7	0.5	0.57	1.28	1.71	1.24	0.85
γ	0.98	0.94	0.88	0.74	0.67	0.75	0.82
L^*, ft	21	13	7.3	3.4	2.5	3.5	5.1
10 log (S^*/A)	16	14	12	8.3	7.1	8.5	10
$L_{w(out)}$	55	48	38	40	38	41	23
−10 log($\pi r L$) + 10	−16	−16	−16	−16	−16	−16	−16
L_p, dB	39	32	22	24	22	25	7

Using round duct eliminates the low-frequency rumble present with rectangular ducts but introduces some mid- and high-frequency noise that can be reduced by adding duct liner as shown.

When sound is not transmitted through the wall of a round duct, it propagates down the duct and may become a problem at another point in the duct system. Round flexible and rigid fiberglass ducts do not have high transmission loss properties because they lack the mass or stiffness associated with round sheet metal ducts.

Whenever duct sound breakout is a concern, fiberglass or flexible round duct should not be used; these ducts have little to no transmission loss, and are essentially transparent to sound. Because Equation (9) does not take into consideration the reduction of sound power over the length of the duct, it will always overestimate the true breakout noise. The overestimation is insignificant for short sections of unlined ductwork, but can become very significant when

Table 28 Ceiling/Plenum/Room Attenuations in dB for Generic Ceiling in T-Bar Suspension Systems

Tile Type	Approximate Density, lb/ft²	Tile Thickness, in.	Octave Midband Frequency, Hz						
			63	125	250	500	1000	2000	4000
Mineral fiber	1.0	5/8	13	16	18	20	26	31	36
	0.5	5/8	13	15	17	19	25	30	33
Glass fiber	0.1	5/8	13	16	15	17	17	18	19
	0.6	2	14	17	18	21	25	29	35
Glass fiber with TL backing	0.6	2	14	17	18	22	27	32	39
Gypsum board tiles	1.8	1/2	14	16	18	18	21	22	22
Solid gypsum board ceiling	1.8	1/2	18	21	25	25	27	27	28
	2.3	5/8	20	23	27	27	29	29	30
Double layer of gypsum board	3.7	1	24	27	31	31	33	33	34
	4.5	11/4	26	29	33	33	35	35	36
Mineral fiber tiles, concealed spline mount.	0.5 to 1	5/8	20	23	21	24	29	33	34

Source: Warnock (1998)

Table 29 TL_in Versus Frequency for Rectangular Ducts

Duct Size, in.	Gage	TL_out, dB Octave Midband Frequency, Hz							
		63	125	250	500	1000	2000	4000	8000
12 × 12	24	16	16	16	25	30	33	38	42
12 × 24	24	15	15	17	25	28	32	38	42
12 × 48	22	14	14	22	25	28	34	40	42
24 × 24	22	13	13	21	26	29	34	40	42
24 × 48	20	12	15	23	26	28	36	42	42
48 × 48	18	10	19	24	27	32	38	42	42
48 × 96	18	11	19	22	26	32	38	42	42

Note: Data are for duct lengths of 20 ft.

the duct is long and has a high rate of attenuation. If the duct is long enough, Equation (9) can yield radiated sound power levels that are higher than the input sound power levels. This is clearly a false result, but it can be avoided by using Equation (16), which provides accurate results for any duct size and length.

Table 28 gives estimates of attenuation of different ceiling construction by octave band. The data can be used to estimate noise reduction by ceilings between ductwork and the receiver.

Break-In Sound Transmission into Ducts. The sound power level associated with sound transmitted into a duct through the duct walls from the space outside the duct is given by

$$L_{w(in)} = L_{w(out)} - \text{TL}_{in} - 3 \qquad (20)$$

where

$L_{w(in)}$ = sound power level of sound transmitted into duct and then transmitted upstream or downstream of point of entry, dB
$L_{w(out)}$ = sound power level of sound incident on outside of duct walls, dB
TL_{in} = duct break-in transmission loss, dB

Values for TL_{in} for rectangular ducts are given in Table 29, for round ducts in Table 30, and for flat oval ducts in Table 31 (Cummings 1983, 1985).

RECEIVER ROOM SOUND CORRECTION

The sound pressure level at a given location in a room caused by a particular sound source is a function of the sound power level and sound radiation characteristics of the sound source, acoustic properties of the room (surface treatments, furnishings, etc.), room volume, and distance between the sound source and point of observation. Two types of sound sources are typically encountered in HVAC system applications: **point** and **line**. Typical point sources are grilles, registers and diffusers; air-valve and fan-powered air terminal units and fan-coil units located in ceiling plenums; and return air openings. Line sources are usually associated with sound breakout from air ducts and long slot diffusers.

For a point source in an enclosed space, classical diffuse-field theory predicts that as the distance between the source and point of

Table 30 Experimentally Measured TL_in Versus Frequency for Circular Ducts

Diameter, in.	Length, ft	Gage	TL_in, dB Octave Midband Frequency, Hz						
			63	125	250	500	1000	2000	4000
Long Seam Ducts									
8	15	26	>17	(31)	39	42	41	32	31
14	15	24	>27	43	43	31	31	28	22
22	15	22	>28	40	30	30	30	24	22
32	15	22	(35)	36	23	23	21	19	35
Spiral Wound Ducts									
8	10	26	>20	>42	>59	>62	53	43	26
14	10	26	>20	>36	44	28	31	32	22
26	10	24	>27	38	20	23	22	19	33
26	10	16	>30	>41	30	29	29	25	38
32	10	22	>27	32	25	22	23	21	37

Note: In cases where background sound swamped sound radiated from duct walls, a lower limit on TL_{in} is indicated by >. Parentheses indicate measurements in which background sound produced greater uncertainty than usual.

Table 31 TL_in Versus Frequency for Flat Oval Ducts

Duct Size, in.	Gage	TL_in, dB Octave Midband Frequency, Hz						
		63	125	250	500	1000	2000	4000
12 × 6	24	18	18	22	31	40	—	—
24 × 6	24	17	17	18	30	33	—	—
24 × 12	24	15	16	25	34	—	—	—
48 × 12	22	14	14	26	29	—	—	—
48 × 24	22	12	21	30	—	—	—	—
96 × 24	20	11	22	25	—	—	—	—
96 × 48	18	19	28	—	—	—	—	—

Note: Data are for duct lengths of 20 ft.

observation is increased, the sound pressure level initially decreases at the rate of 6 dB per doubling of distance. At some point, the reverberant sound field begins to dominate and the sound pressure level remains at a constant level.

For point sound sources in **reflective unfurnished rooms**, the classic diffuse equation for converting sound power to pressure could be used:

$$L_p = L_W + 10 \log(Q/4\pi r^2 + 4/R) + 10.5 \qquad (21)$$

where

L_p = sound pressure level, dB (re 20 μPa)
L_W = sound power level, dB (re 10^{-12} W)
Q = directivity of sound source, dimensionless; see Figure 26
r = distance from source, ft

Table 32 Values for *A* in Equation (22)

Room Volume, ft^3	Value for *A*, dB Octave Midband Frequency, Hz						
	63	125	250	500	1000	2000	4000
1500	4	3	2	1	0	−1	−2
2500	3	2	1	0	−1	−2	−3
4000	2	1	0	−1	−2	−3	−4
6000	1	0	−1	−2	−3	−4	−5
10,000	0	−1	−2	−3	−4	−5	−6
15,000	−1	−2	−3	−4	−5	−6	−7

Table 33 Values for *B* in Equation (22)

Distance from Sound Source, ft	Value for *B*, dB
3	5
4	6
5	7
6	8
8	9
10	10
13	11
16	12
20	13

R = sum of all surface areas and their corresponding absorption coefficients [$S\alpha/(1 - \alpha)$], ft^2

A further discussion of assumptions used in converting power to pressure is available in Chapter 7 of the 2005 *ASHRAE Handbook—Fundamentals*.

However, investigators have found that diffuse-field theory does not apply in rooms with furniture or other sound-scattering objects (Schultz 1985; Thompson 1981). Instead, sound pressure levels decrease at the rate of around 3 dB per doubling of distance between sound source and point of observation. Generally, a true reverberant sound field does not exist in small rooms (room volumes less than 15,000 ft^3). In larger rooms reverberant fields usually exist, but typically at distances from the sound sources that are significantly greater than those predicted by diffuse-field theory.

Most **normally furnished rooms** of regular proportions have acoustic characteristics that range from *average* to *medium dead*. These usually include carpeted rooms with sound-absorptive ceilings. If such a room has a volume less than 15,000 ft^3 and the sound source is a single point source, sound pressure levels associated with the sound source can be obtained from (Schultz 1985).

$$L_p = L_w + A - B \tag{22}$$

where

L_p = sound pressure level at specified distance from sound source, dB (re 20 μPa)
L_w = sound power level of sound source, dB (re 10^{-12} W)

Values for *A* and *B* are given in Tables 32 and 33.

If a normally furnished room has a volume greater than 15,000 ft^3 and the sound source is a single point source, sound pressure levels associated with the sound source can be obtained from

$$L_p = L_w - C - 5 \tag{23}$$

Values for *C* are given in Table 34. Equation (23) can be used for room volumes of up to 150,000 ft^3, with accuracy typically within 2 to 5 dB.

Distributed Array of Ceiling Sound Sources

In many office buildings, air supply outlets are located flush with the ceiling of the conditioned space and constitute an array of distributed ceiling sound sources. The geometric pattern depends on

Table 34 Values for *C* in Equation (23)

Distance from Sound Source, ft	Value for *C*, dB Octave Midband Frequency, Hz						
	63	125	250	500	1000	2000	4000
3	5	5	6	6	6	7	10
4	6	7	7	7	8	9	12
5	7	8	8	8	9	11	14
6	8	9	9	9	10	12	16
8	9	10	10	11	12	14	18
10	10	11	12	12	13	16	20
13	11	12	13	13	15	18	22
16	12	13	14	15	16	19	24
20	13	15	15	16	17	20	26
25	14	16	16	17	19	22	28
32	15	17	17	18	20	23	30

Table 35 Values for *D* in Equation (24)

Floor Area per Diffuser, ft^2	Value for *D*, dB Octave Midband Frequency, Hz						
	63	125	250	500	1000	2000	4000
Ceiling height 8 to 9 ft							
100 to 150	2	3	4	5	6	7	8
200 to 250	3	4	5	6	7	8	9
Ceiling height 10 to 12 ft							
150 to 200	4	5	6	7	8	9	10
250 to 300	5	6	7	8	9	10	11
Ceiling height 14 to 16 ft							
250 to 300	7	8	9	10	11	12	13
350 to 400	8	9	10	11	12	13	14

the floor area served by each outlet, ceiling height, and thermal load distribution. In interior zones of a building where thermal load requirements are essentially uniform, air delivery per outlet is usually the same throughout the space; thus, these outlets emit nominally equal sound power levels. One way to calculate sound pressure levels in a room with a distributed array is to use Equation (22) or (23) to calculate the sound pressure levels for each individual air outlet at specified locations in the room and then logarithmically add the sound pressure levels for each diffuser at each observation point. This procedure can be very tedious for a room with a large number of ceiling air outlets.

For a distributed array of ceiling sound sources (air outlets) of nominally equal sound power, room sound pressure levels tend to be uniform in a plane parallel to the ceiling. Although sound pressure levels decrease with distance from the ceiling along a vertical axis, they are nominally constant along any selected horizontal plane. Equation (24) simplifies calculation for a distributed ceiling array. For this case, use a reference plane 5 ft above the floor.

Thus, $L_{p(5)}$ is obtained from

$$L_{p(5)} = L_{W(s)} - D \tag{24}$$

where

$L_{p(5)}$ = sound pressure level at distance of 5 ft above floor, dB (re 20 μPa)
$L_{W(s)}$ = sound power level of single diffuser in array, dB (re 10^{-12} W)

Values of *D* are given in Table 35.

Nonstandard Rooms

The previous equations assume that the acoustical characteristics of a room range from average to medium dead, which is generally true of most rooms. However, some rooms may be acoustically

medium live to *live* (i.e., they have little sound absorption). These rooms may be sports or athletic areas, concert halls, or other rooms designed to be live, or they may be rooms that are improperly designed from an acoustic standpoint. The previous equations should not be used for acoustically live rooms because they can overestimate the decrease in sound pressure levels associated with room sound correction by as much as 10 to 15 dB. When these or other types of nonstandard rooms are encountered, it is best to use the services of an acoustical engineer.

Line Sound Sources

Sound from breakout from air ducts or long slot diffusers may be modeled as line sources. To convert sound power levels to the corresponding sound pressure levels in a room for such cases, the following equation may be used:

$$L_p = L_W + 10 \log(1/\pi r L + 4/R) + 10.5 \qquad (25)$$

where

L_p = sound pressure level, dB (re 20 µPa)
L_W = sound power level, dB (re 10^{-12} W)
  r = distance from source, ft
  L = length of line source
  R = room constant = sum of all surface areas and their corresponding absorption coefficients [$S\alpha/(1-\alpha)$], ft²

This is the classic diffuse room equation for a line source, and may not produce accurate results for standard nondiffuse rooms. Unfortunately, no information is available at this time on how to correct more accurately for the effect of the receiver room on line sources.

SOUND CONTROL FOR OUTDOOR EQUIPMENT

Outdoor mechanical equipment should be carefully selected, installed, and maintained to minimize sound radiated by the equipment, and to comply with local noise codes. Equipment with strong tonal components is more likely to provoke complaints than equipment with a broadband noise spectrum.

Sound Propagation Outdoors

If the equipment sound power level spectrum and ambient sound pressure level spectrum are known, the contribution of the equipment to the sound level at any location can be estimated by analyzing the sound transmission paths involved. When there are no intervening barriers and no attenuation because of berms, ground absorption, or atmospheric effects, the principal factor in sound pressure level reduction is distance. The following equation may be used to estimate the sound pressure level of equipment at a distance from it and at any frequency when the sound power level is known:

$$L_p = L_w + 10 \log Q - 20 \log d - 11 \qquad (26)$$

where

  d = distance from acoustic center of source to distant point, ft
L_p = sound pressure level at distance d from sound source, dB
L_w = sound power level of sound source, dB
  Q = directivity factor associated with way sound radiates from sound source (see Figure 26)

Equation (26) does not apply where d is less than twice the maximum dimension of the sound source. L_p may be low by up to 5 dB where d is between two and five times the maximum sound source dimension. Also, if the distance is greater than about 500 ft, wind, thermal gradients, and atmospheric sound absorption need to be considered.

For complex cases, refer to texts on acoustics (e.g., Beranek 1971) and international standards such as ISO *Standard* 9613-2.

Sound Barriers

A sound barrier is a solid structure that intercepts the direct sound path from a sound source to a receiver. It reduces the sound pressure level within its shadow zone. Figure 27 illustrates the geometrical aspects of an outdoor barrier where no extraneous surfaces reflect sound into the protected area. Here the barrier is treated as an intentionally constructed noise control structure. If a sound barrier is placed between a sound source and receiver location, the sound pressure level L_p in Equation (26) is reduced by the **insertion loss (IL)** associated with the barrier.

Table 36 gives the insertion loss of an outdoor ideal solid barrier when no surfaces reflect sound into the shadow zone, and the sound transmission loss of the barrier wall or structure is at least 10 dB greater at all frequencies than the insertion loss expected of the barrier. The path-length difference referred to in Table 36 is given by

$$\text{Path-length difference} = A + B - D \qquad (27)$$

where A, B, and D are as specified in Figure 27.

The limiting value of about 24 dB is caused by sound scattering and refracting into the shadow zone formed by the barrier. Practical

Table 36   Insertion Loss Values of Ideal Solid Barrier

Path-Length Difference, ft	Insertion Loss, dB — Octave Midband Frequency, Hz							
	31	63	125	250	500	1000	2000	4000
0.01	5	5	5	5	5	6	7	8
0.02	5	5	5	5	5	6	8	9
0.05	5	5	5	5	6	7	9	10
0.1	5	5	5	6	7	9	11	13
0.2	5	5	6	8	9	11	13	16
0.5	6	7	9	10	12	15	18	20
1	7	8	10	12	14	17	20	22
2	8	10	12	14	17	20	22	23
5	10	12	14	17	20	22	23	24
10	12	15	17	20	22	23	24	24
20	15	18	20	22	23	24	24	24
50	18	20	23	24	24	24	24	24

UNIFORM SPHERICAL RADIATION, NO REFLECTING SURFACES
Q = 1

UNIFORM HEMISPHERICAL RADIATION, SINGLE REFLECTING SURFACE
Q = 2

UNIFORM RADIATION OVER 1/4 OF A SPHERE, TWO REFLECTING SURFACES
Q = 4

UNIFORM RADIATION OVER 1/8 OF A SPHERE, THREE REFLECTING SURFACES
Q = 8

LARGE SOURCE, Q MAY VARY WITH DIRECTION
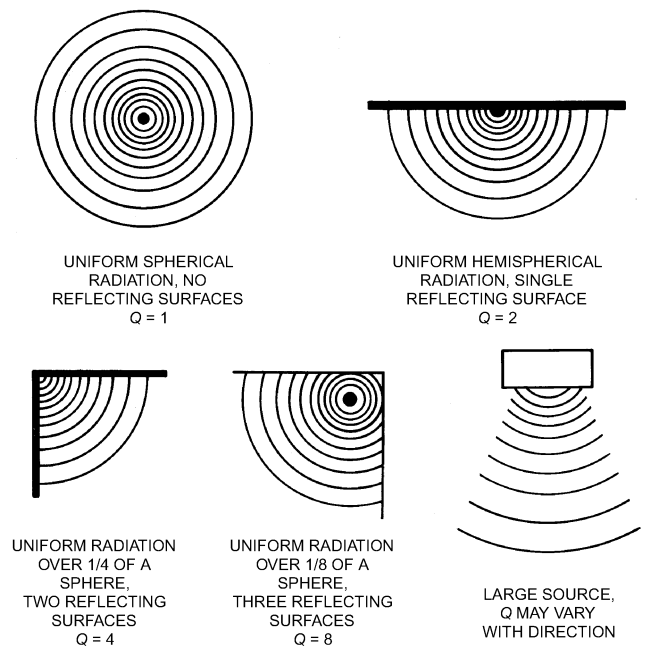
Fig. 26   Directivity Factors for Various Radiation Patterns

constructions such as size and space restrictions often limit sound barrier performance to 10 to 15 dBA. For large distances outdoors, this scattering and bending of sound waves into the shadow zone reduces barrier effectiveness. At large distances, atmospheric conditions can significantly affect sound path losses by amounts even greater than those provided by the barrier, with typical differences of 10 dBA. For a conservative estimate, the height of the sound source location should be taken as the topmost part of the sound source, and the height of the receiver should be taken as the topmost location of a sound receiver, such as the top of the second-floor windows in a two-floor house or at a height of 5 ft for a standing person.

Reflecting Surfaces. No other surfaces should be located where they can reflect sound around the ends or over the top of the barrier into the barrier shadow zone. Figure 28 shows examples of reflecting surfaces that can reduce the effectiveness of a barrier wall.

Width of Barrier. Each end of the barrier should extend horizontally beyond the line of sight from the outer edge of the source to the outer edge of the receiver position by a distance of at least three times the path-length difference. Near the ends of the barrier, the effectiveness of the noise isolation is reduced because some sound is diffracted over the top and around the ends. Also, some
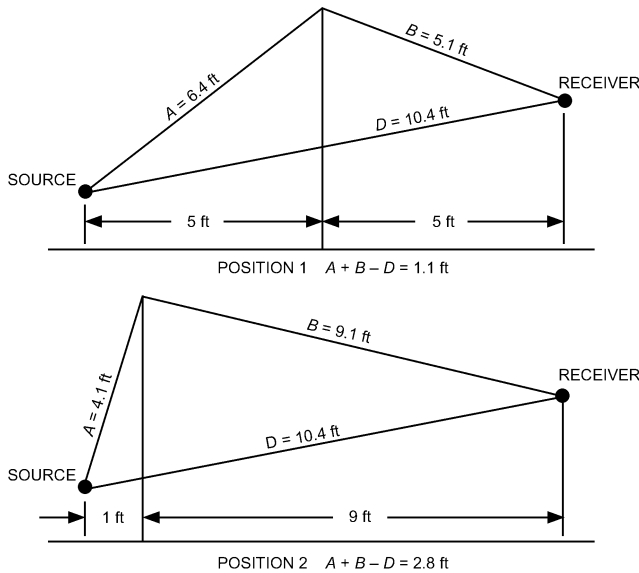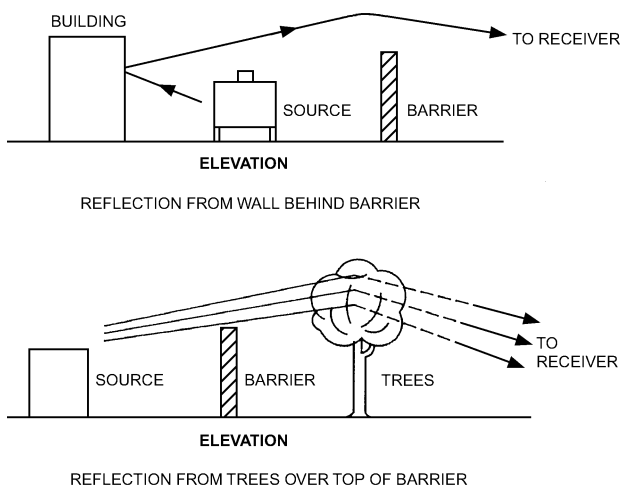
sound is reflected or scattered from various nonflat surfaces along the ground near the ends of the barrier. In critical situations, the barrier should completely enclose the sound source to eliminate or reduce the effects of reflecting surfaces.

Reflection from a Barrier. A large, flat reflecting surface, such as a barrier wall, may reflect more sound toward the source than there would have been with no wall present. If the wall produces no special focusing effect, reflections from the wall will produce levels on the side of the barrier facing the source that are 2 to 3 dB higher. Using acoustical absorption on the barrier surface (source side) reduces this increase.

FUME HOOD DUCT DESIGN

Fume hood exhaust systems are often the major sound source in a laboratory. The exhaust system may consist of individual exhaust fans ducted to separate fume hoods, or a central exhaust fan connected through a collection duct system (commonly known as a manifold) to a large number of hoods. In either case, a redundancy system consisting of two fans might be used. Other sound sources are the air terminal unit serving the hood and aerodynamically generated noise in the ducts. Sound pressure levels produced in the laboratory space should be estimated using procedures described in this section and manufacturer-supplied noise emission data. Recommended noise level design criteria for laboratory spaces using fume hoods are given in Table 42.

To minimize static pressure loss and blower power consumption in a duct system, fume hood ducts should be sized to allow rated airflow at no greater than 2000 fpm or at a velocity consistent with regulatory requirements. Duct velocities over 2000 fpm should be avoided for acoustical reasons and to conserve energy. At this speed, the design criteria given in Table 42 are unlikely to be met, even with a silenced fan(s).

Noise control measures for fume hood systems include the following:

Fan(s)
- Where conditions allow, use backward-inclined or forward-curved fans instead of radial-blade fans.
- Select fan(s) to operate at a low tip speed and maximum efficiency.
- Try to run redundant fans at reduced capacity instead of operating one fan at full capacity.

Manifold
- Design the manifold upstream of the fan(s) to double as an unlined acoustic plenum. Fan low-frequency noise can be reduced

Fig. 27   Noise Barrier
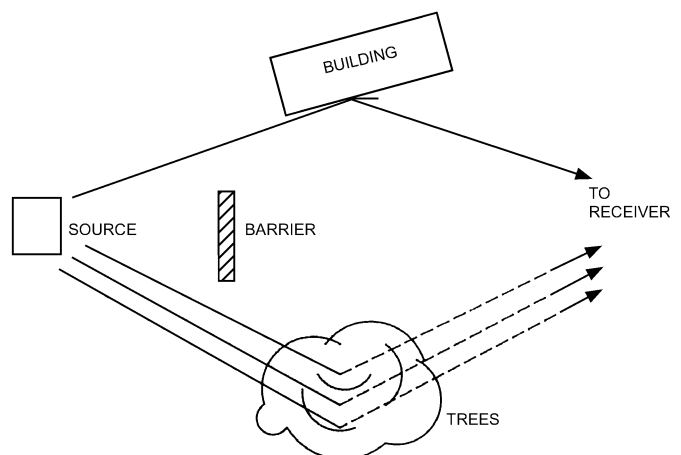
Fig. 28   Reflecting Surfaces That Can Diminish Barrier Effectiveness

when the manifold is parallel-piped, with large surface area compared to the cross-sectional area of the fume hood ducts connecting to it.

Duct silencers
- Use prefabricated duct silencers or sections of lined ducts where conditions allow. In addition to galvanized steel, silencers can be fabricated with stainless steel, aluminum, or plastic.

Duct design
- Design duct elements such as elbow and junctions with low friction to minimize duct pressure loss and aerodynamically generated noise.

Air terminal unit
- Allow 2 to 3 ft of straight duct upstream and downstream from the terminal unit to reduce aerodynamically generated noise at the unit.

Fume hood location
- Where possible, locate fume hoods in private alcoves to reduce lab occupant's noise exposure.

All potential noise control measures should be carefully evaluated for compliance with applicable codes, safety requirements, and corrosion resistance requirements of the specific fume hood system. In addition, vibration isolation for fume hood exhaust fans is generally required. However, for some laboratory facilities, particularly those with highly vibration-sensitive instruments such as electron microscopes, vibration control can be critical, and a vibration specialist should be consulted.

MECHANICAL EQUIPMENT ROOM SOUND ISOLATION

Locating HVAC equipment in a common room allows the designer to control noise affecting nearby spaces. Often, these spaces have background noise level criteria that dictate the type of construction and treatment necessary to achieve sufficient reduction in equipment noise transmitted to other spaces.

The most effective noise control measure for indoor mechanical equipment rooms is to locate them as far away as possible from noise-sensitive areas. In some cases, this requires a separate structure, such as a central chiller plant, to house equipment. Subterranean basement locations are typically best for noisy equipment because the basement usually affects the fewest adjacent locations. Penthouse equipment rooms are common but can create significant challenges for noise and vibration isolation. Rooms containing air-handling units should provide sufficient room for the equipment and associated ductwork to allow smooth transitions and full-radius curved elbows. A building corner location can work well by reducing the number of adjacent interior spaces and the amount of associated outside-air ductwork. Using adjacent spaces such as corridors, closets, and storage rooms as buffer zones can provide effective noise control. A common mistake in locating mechanical equipment rooms is to position the room in the core of the building between a stairway, an elevator shaft, and a telecommunications closet, leaving only one wall where supply and return air ductwork can enter and leave the room. This leads to high-velocity air in the ductwork and high static pressures for fans to overcome, leading to higher noise levels.

Once the mechanical equipment room location has been established, the amount of noise created in the room should be assessed and appropriate constructions selected for walls, ceilings, and floors. Concrete masonry units of various available thickness and densities are often used for their durability and effectiveness in reducing low-frequency noise levels. Typically, heavier and thicker materials contain more sound within the space. Special masonry units that provide a limited amount of acoustical absorption using slotted openings and resonator cavities can also be used. The sound

isolation of a masonry wall can be significantly improved by using furred-out gypsum wallboard and insulation in cavities. Chillers and other equipment with very high noise levels are best situated in rooms with concrete masonry unit walls.

Often, because of structural issues and weight limitations, mechanical equipment room walls are built from gypsum wallboard on metal or wood studs. To adequately attenuate low-frequency noise, sufficient mass and thickness must be provided in the wall partition construction. This typically entails using multiple levels of gypsum wallboard on both sides of the wall with batt insulation in the cavities. Where greater levels of noise reduction are required, walls are built on double, staggered-stud construction using two separate rows of studs on separate tracks with multiple layers of gypsum wallboard and batt insulation in the cavities.

For all types of walls, service penetrations should be fully caulked and sealed. Pipes, ducts, and conduits that penetrate walls, ceilings, or floors of mechanical rooms should be acoustically treated. Typically, a 0.5 in. gap around the penetrating element is filled with an appropriate material such as mineral fiber insulation. The penetration is then sealed airtight with resilient caulk (Figure 29).

Doors into mechanical equipment rooms are frequently the weak link in the enclosure. Where noise control is important, the doors should be as heavy as possible, gasketed around the perimeter, have no grilles or other openings, and be self-closing. If they lead to sensitive spaces, two doors separated by a 3 to 10 ft corridor may be necessary.

Penetration of Walls by Ducts

Ducts passing through the mechanical equipment room enclosure pose an additional problem. Sound can be transmitted to either side of the wall through duct walls. Airborne sound in the mechanical room can be transmitted into the duct (break-in) and enter an adjacent space by reradiating (breakout) from duct walls, even if the duct contains no grilles, registers, diffusers, or other openings.

Sound levels in ducts close to fans are usually high. Sound can come not only from the fan but also from pulsating duct walls, excessive air turbulence, and air buffeting caused by tight or restricted fan airflow entrance or exit configurations. Duct layout for good aerodynamics and airflow conditions should minimize low-frequency sound generation, which, once generated, is difficult or impossible to remove, especially near noise-sensitive areas. Avoid elements conducive to increased breakout noise transmission and/or with a tendency to vibrate at low frequencies because of non-laminar airflow. Round ductwork is most resistant to these problems, followed by square and rectangular ducts with aspect ratios less than 2:1. Heavier-than-normal gage metal ductwork, such as 16 ga within the mechanical room and over noise-sensitive spaces, can also be used.

Mechanical Chases

Mechanical chases and shafts should be acoustically treated the same way as mechanical equipment rooms, especially if they contain noise-producing ductwork, pipes, and equipment such as fans and pumps. The shaft should be closed at the mechanical equipment room, and shaft wall construction must provide sufficient reduction of mechanical noise from the shaft to noise-sensitive areas to obtain acceptable noise levels. Chases should not be allowed to become "speaking tubes" between spaces requiring different acoustical environments. Crosstalk through the shaft must be prevented. Pipes, ducts, conduits, or equipment should be vibration-isolated so that mechanical vibration and structureborne noise is not transmitted to the shaft walls and into the building structure.

When mechanical equipment rooms are used as supply or return plenums, all openings into the equipment room plenum space may
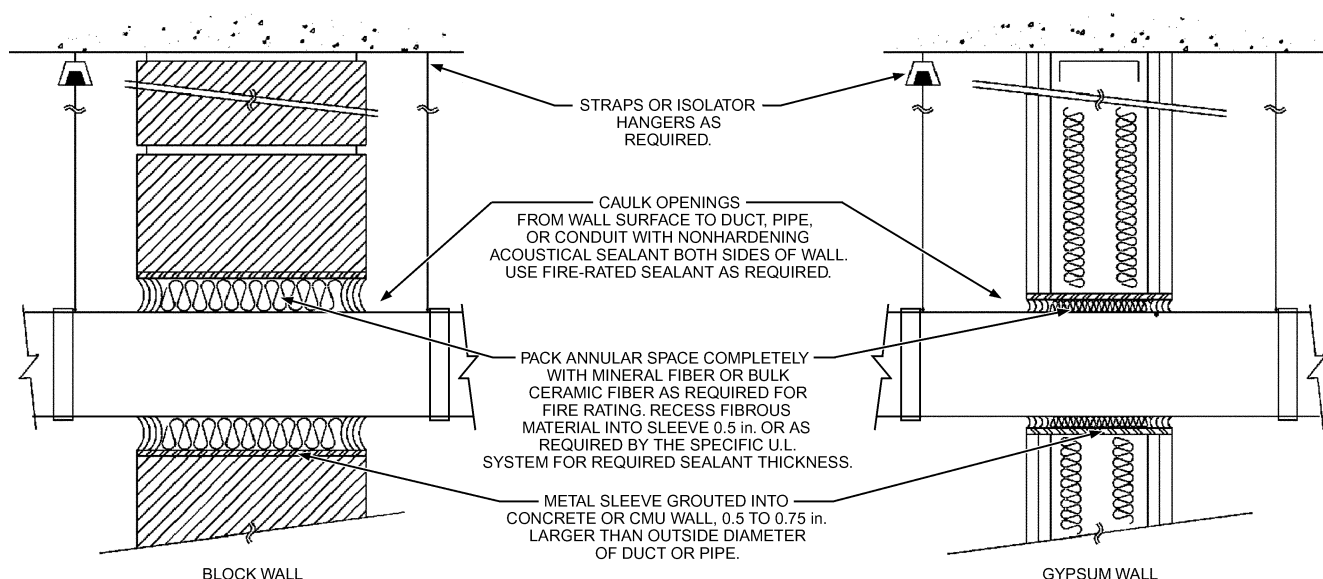
Fig. 29   Duct, Conduit, and Pipe Penetration Details

Table 37   Sound Transmission Class (STC) and Transmission Loss Values of Typical Mechanical Equipment Room Wall, Floor, and Ceiling Types, dB

Room Construction Type	STC	Octave Midband Frequency, Hz						
		63	125	250	500	1000	2000	4000
8 in. CMU*	50	35	35	41	44	50	57	64
8 in. CMU with 5/8 in. GWB* on furring strips	53	33	32	44	50	56	59	65
5/8 in. GWB on both sides of 3 5/8 in. metal studs	38	18	16	33	47	55	43	47
5/8 in. GWB on both sides of 3 5/8 in. metal studs with fiberglass insulation in cavity	49	16	23	44	58	64	52	53
2 layers of 5/8 in. GWB on both sides of 3 5/8 in. metal studs with fiberglass insulation in cavity	56	19	32	50	62	67	58	63
Double row of 3 5/8 in. metal studs, 1 in. apart, each with 2 layers of 5/8 in. GWB and fiberglass insulation in cavity	64	23	40	54	62	71	69	74
6 in. solid concrete floor/ceiling	53	40	40	40	49	58	67	76
6 in. solid concrete floor with 4 in. isolated concrete slab and fiberglass insulation in cavity	72	44	52	58	73	87	97	100
6 in. solid concrete floor with two layers of 5/8 in. GWB hung on spring isolators with fiberglass insulation in cavity	84	53	63	70	84	93	104	105

Note: Actual material composition (e.g., density, porosity, stiffness) affects transmission loss and STC values.
*CMU = concrete masonry unit; GWB = gypsum wallboard.

require noise control treatment, especially if any sound-critical space is immediately adjacent. This is particularly true if the space above an acoustical tile ceiling just outside the equipment room is used as a return air plenum. Most acoustical tile ceilings are almost acoustically transparent at low frequencies.

Often, supply ducts are run inside a chase that is also used for return air. It is best to attenuate supply and return paths at the fan rather than let duct breakout noise require additional noise control at the chase return air inlets. Care should be used to prevent turbulent noise generation in the supply duct through proper supply duct design.

Special Construction Types

Sound transmission loss values for some typical constructions are given in Table 37. These data are compiled from controlled laboratory tests and represent a condition typically superior to that found in field installations, because the in situ acoustical performance of any wall, floor, or ceiling is adversely affected by flanking paths, holes, penetrations, and other anomalies. Flanking paths include intersections of the wall, floor, or ceiling surface with another wall, floor, or ceiling that is structurally connected. Higher levels of sound isola-

tion can be achieved by decoupling the surfaces and using double-walled, floating floor, or barrier-ceiling constructions.

Floating Floors and Barrier Ceilings

Correctly installed floating floors and barrier ceilings can provide very high levels of sound isolation, allowing mechanical equipment rooms to be placed adjacent to noise-sensitive spaces. Like double-walled construction, these configurations decouple two surfaces by providing separate supporting structures. However, these types of construction can add significant cost and coordination complexity and should be carefully evaluated.

In a floating floor, the upper floor slab is typically a 4 in. concrete slab resting on vibration isolators supported by the subfloor (typically another concrete slab of appropriate thickness). An air gap is maintained between the two slabs and resilient materials are used around the upper slab's perimeter to decouple it from surrounding walls. Any heavy equipment should be supported from the subfloor slab, not the floating floor.

Similarly, barrier ceilings are typically composed of multiple layers of gypsum wallboard attached to a frame suspended from the structure above with vibration-isolating hangers. Ductwork,

piping, and other equipment is not supported from the floating ceiling but from the structure above it. This requires careful coordination of hangers and supports before installing the acoustical barrier ceiling.

Design and selection of the floating floor or ceiling should be carefully considered to properly support the dead and live loads it must carry. The floating system (floor or ceiling) *is not meant as a means of equipment vibration isolation and serves primarily to control airborne sound transmission*. Acoustical performance of the floating system depends greatly on construction quality, which requires careful coordination between all trades. All penetrations and intersections with other surfaces must allow the floor or ceiling to float without any rigid connections. This typically entails maintaining clearances of at least 0.25 in. and filling all gaps with resilient materials such as nonhardening caulk.

Sound Transmission in Return Air Systems

The fan return air system provides a sound path (through ducts or a ceiling plenum) between a fan and occupied rooms. Where there is a direct opening to the mechanical equipment room from the ceiling plenum, sound levels in adjacent spaces can be high, originating from the fan and other sources in the mechanical equipment room. Low system attenuation between the mechanical equipment room and adjacent spaces exacerbates the problem.

Fan intake sound power levels control sound in ducted return air systems; sound power levels of the fan intake and casing-radiated noise components affect plenum return air systems. In some installations, sound from other equipment located in the mechanical equipment room may also radiate through the wall opening and into adjacent spaces. Good design yields room return air system sound levels that are approximately 5 dB below the corresponding room supply air system sound levels.

When sound levels in spaces adjacent to mechanical equipment rooms are too high, noise control measures must be provided. The controlling sound paths between the mechanical equipment room and adjacent spaces must be identified. Ducted return air systems can be modified using methods applicable to ducted supply systems. Ceiling plenum return systems should only be used for spaces that are remote from mechanical equipment rooms.

Ceiling plenum systems may require additional modifications. Prefabricated silencers can be effective when installed at the mechanical equipment room wall opening or at the suction side of the fan. Improvements in ceiling transmission loss are often limited by typical ceiling penetrations and lighting fixtures. Modifications to the mechanical equipment room wall can be effective for some constructions. Adding acoustical absorption in the mechanical equipment room reduces build-up of reverberant sound energy in this space; however, this typically reduces high-frequency noise by a maximum of 4 dB and low-frequency noise only slightly in areas near the return opening.

Sound Transmission Through Ceilings

When terminal units, fan-coil units, air-handling units, ducts, or return air openings to mechanical equipment rooms are located in a ceiling plenum above a room, sound transmission through the ceiling system can be high enough to cause excessive noise levels in that room. There is no standard test procedure for measuring direct transmission of sound through ceilings from sources close to the ceiling. As a result, ceiling product manufacturers rarely publish data that can be used in calculations. The problem is complicated by the presence of light fixtures, diffusers, grilles, and speakers that reduce the ceiling's transmission loss. Experiments have shown that, for ceiling panels supported in a T-bar grid system, leakage between the panels and grid is the major transmission path; differences among panel types are small, and light fixtures, diffusers, etc., have only a localized effect.

Table 38　Environmental Correction to Be Subtracted from Device Sound Power

Octave Band Frequency, Hz						
63	125	250	500	1000	2000	4000
4	2	1	0	0	0	0

Table 39　Compensation Factors for Source Area Effect

Area range, ft^2			
63 Hz	125 Hz	250 Hz	Adjustment, dB
<2.6	<2.2		–3
2.8 to 4.9	2.4 to 4.6	<2.3	–2
5.1 to 7.2	4.9 to 7.1	2.7 to 6.3	–1
7.4 to 9.4	7.3 to 9.5	6.7 to 10.3	0
9.7 to 11.7	9.8 to 12.0	10.7 to 14.3	1
11.9 to 14.0	12.2 to 14.4	14.7 to 18.3	2
14.2 to 16.3	14.6 to 16.8	18.7 to 22.3	3
16.5 to 18.5	17.1 to 19.3		4
18.8 to 20.8	19.5 to 21.7		5
21.0 to 23.1			6

Note: Find correct area in each frequency column and read adjustment from last column on right.

To estimate room sound pressure levels associated with sound transmission through the ceiling, sound power levels in the ceiling plenum must be adjusted to account for the transmission loss of the ceiling system and plenum. Measured data must also be adjusted to account for sound absorption in the room. The procedures given here are based on ASHRAE research (Warnock 1998):

1. Obtain octave band radiated sound power levels of device.
2. Subtract environmental correction from Table 38.
3. Calculate surface area of bottom panel of source closest to ceiling tiles (ft^2).
4. From Table 39, find adjustment to be subtracted from sound power values at three frequencies given there.
5. Select ceiling/plenum attenuation from Table 28 according to ceiling type in use.
6. Subtract the three sets of values, taking account of sign where necessary, from sound power values. The result is the average sound pressure level in the room.
7. The sound field in the room may be assumed as uniform up to distances of 16 ft from the source.

Example 6. A terminal unit with an area of 14 ft^2 and a known sound power level is to be used above a standard 5/8 in. thick mineral fiber ceiling system in a T-bar grid. What room sound pressure levels can be expected?

Solution:

		Octave Band Frequency, Hz						
Step		63	125	250	500	1000	2000	4000
1	Sound power	71	71	65	55	54	53	45
2	Environmental (Table 38)	–4	–2	–1	0	0	0	0
4	Area adjustment (Table 39)	–2	–2	–1	0	0	0	0
5	Ceiling/plenum (Table 28)	–13	–15	–17	–19	–25	–30	–33
6	Room sound pressure levels, dB	52	52	46	36	29	23	12

RECEIVER CONSIDERATIONS

Indoor Sound Criteria

HVAC-related sound is often the major source of background noise in indoor spaces. Whether an occupant considers the background noise acceptable or not generally depends on two factors. First is the **perceived loudness** of the noise relative to that of normal

Table 40   Comparison of Sound Rating Methods*

Method	Overview	Considers Speech Interference Effects	Evaluates Sound Quality	Components Presently Rated by Each Method
NC	Can rate components No quality assessment Does not evaluate low-frequency rumble	Yes	No	Air terminals Diffusers
RC	Used to evaluate systems Should not be used to evaluate components Can be used to evaluate sound quality Provides some diagnostic capability	Yes	Yes	
dBA	No quality assessment Frequently used for outdoor noise ordinances	Yes	No	Cooling towers Water chillers Condensing units
NCB	Can rate components Some quality assessment	Yes	Yes	
RC Mark II	Evaluates sound quality Provides improved diagnostics capability	Yes	Yes	

*None of the described methods effectively address potential effect of sound level fluctuations and presence of discrete tones.

activities; if it is clearly noticeable, it is likely to be distracting and cause complaint. Second is the **quality** of the background noise; if the noise is perceived as a rumble, roar, hiss, or tone, this may result in complaints of annoyance and stress. The frequency spectrum is then said to be unbalanced.

The acoustical design must ensure that HVAC noise is of sufficiently low level and unobtrusive quality so as not to interfere with occupancy use requirements. If background noise reduces speech intelligibility, for example, complaints of lost productivity can result. Accordingly, methods of rating HVAC-related noise should assess both perceived loudness and quality.

In the initial design and final commissioning phases of an HVAC system, sound criteria are needed to determine the degree of noise impact and the amount of noise and vibration reduction required for acceptable background sound and vibration levels based on occupancy usage. This section is intended primarily to assist with the design phase and provide limited assistance with diagnosing problems. Detailed diagnosis of problems may require the assistance of an acoustical consultant or an engineer experienced in HVAC system noise and vibration analysis. The section on Testing for Sound and Vibration in Chapter 37 should be consulted for the commissioning phase.

This section presents ways to rate or measure the sound to determine acceptability. The information should help the design engineer select the most appropriate background noise rating method for a specific project. Current methods include the traditional A-weighted sound pressure level (dBA) and tangent noise criteria (NC), the more recent room criterion (RC) and balanced noise criterion (NCB), and the newer RC Mark II. Each method was developed based on data for specific applications; hence, not all are equally suitable for rating HVAC-related noise in the variety of applications encountered. The preferred sound rating methods generally comprise two distinct parts: a family of criterion curves (specifying sound levels by octave bands), and a companion procedure for rating the calculated or measured sound data relative to the criterion curves.

Ideally, HVAC-related background noise should have the following characteristics:

• Balanced contributions from all parts of the sound spectrum with no predominant bands of noise
• No audible tones such as a hum or whine
• No fluctuations in level such as a throbbing or pulsing

Unfortunately, at this time there is no acceptable and simple process to characterize the effects of audible tones and level fluctuations, so none of these rating methods address these issues. Table 40 summarizes the essential differences, advantages, and dis-advantages of rating methods used to characterize HVAC-related background noise.

NC: Noise Criteria Method. The NC method for rating noise, described in Chapter 7 of the 2005 *ASHRAE Handbook—Fundamentals*, has been used for more than 30 years. It is a single-number rating that is somewhat sensitive to the relative loudness and speech interference properties of a given noise spectrum. The method consists of a family of criterion curves extending from 63 to 8000 Hz, and a **tangency rating procedure**. The criterion curves define the limits of octave band spectra that must not be exceeded to meet occupant acceptance in certain spaces. The rating is expressed as NC followed by a number (e.g., NC 40). The octave midband frequency of the point at which the spectrum is tangent to the NC curve should be reported.

Widely used and understood, the NC method is sensitive to level and has the disadvantage that the tangency method used to determine the rating does not require that the noise spectrum approximate the shape of the NC curves. Thus, different-sounding noises can have the same numeric rating, but rank differently on the basis of sound quality. With the advent of VAV systems, excessive low-frequency noise below the 63 Hz octave band has become a serious problem, and the NC rating method does not address this (Ebbing and Blazier 1992). If the NC method is chosen, sound levels at frequencies below 63 Hz must be evaluated by other means. Specifications and design criteria can further restrict allowable sound levels.

In many HVAC systems that do not produce excessive low-frequency noise and strong discernable pure tones, the NC rating correlates relatively well with occupant satisfaction if sound quality is not a significant concern. NC rating is often used because of its simplicity.

RC: Room Criteria Method. ASHRAE previously recommended the room criterion (RC) curves (ANSI *Standard* S12.2; Chapter 43 in the 1995 *ASHRAE Handbook–HVAC Systems and Equipment*; Blazier 1981a, 1981b) as the preferred method for rating HVAC system related noise. The RC curves were intended to establish HVAC system design goals. *The revised RC Mark II method is now preferred.*

The RC method is a family of criterion curves and a rating procedure. The shape of these curves (similar to those for RC Mark II in Figure 31) represents a well-balanced, bland-sounding spectrum, including two additional octave bands (16 and 31.5 Hz) added to deal with excessive low-frequency noise. This rating procedure assesses background noise in spaces, both on the basis of its effect on speech, and on subjective sound quality. The rating value is expressed as RC followed by a number to show the level of the noise and a letter to indicate the quality [e.g., RC 35(N), where N denotes
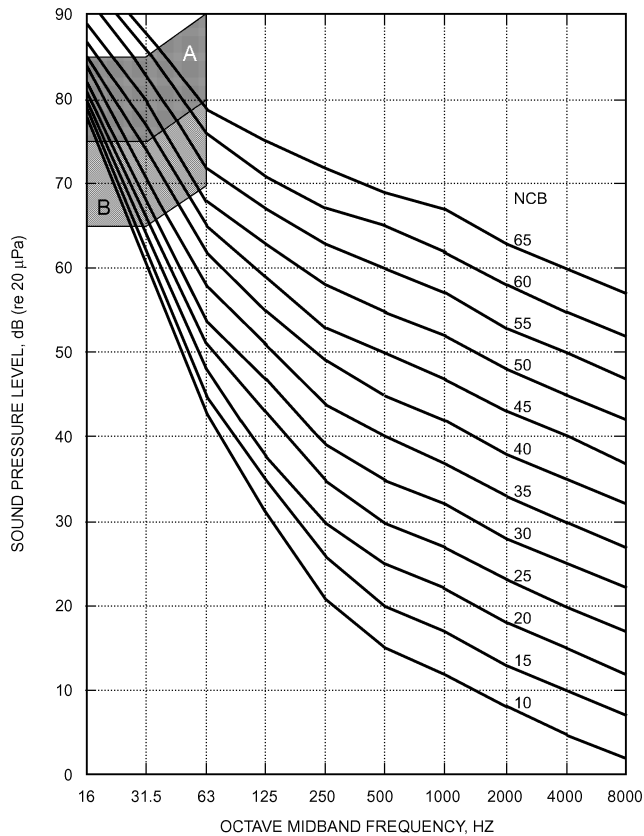
Fig. 30   NCB Noise Criterion Curves

Note:
- Noise levels for lightweight wall and ceiling constructions:
  - In shaded region B are likely to generate vibration that may be perceptible. There is a slight possibility of rattles in light fixtures, doors, windows, etc.
  - In shaded region A have a high probability of generating easily perceptible noise-induced vibration. Audible rattling in light fixtures, doors, windows, etc. may be anticipated.
- Regions LF, MF, and HF are explained in the text.
- Solid dots are sound pressure levels for the example discussed in the text.

Fig. 31   Room Criterion Curves, Mark II

a desired neutral]. The RC method includes evaluation of the potential for noise-induced vibration from excessive airborne sound levels at and below 63 Hz.

dBA: A-Weighted Sound Level. The A-weighted sound level (described in Chapter 7 of the 2005 *ASHRAE Handbook—Fundamentals*) has been used for more than 40 years as a single-number measure of the relative loudness of noise, especially for outdoor environmental noise standards. The rating is expressed as a number followed by dBA (e.g., 40 dBA).

A-weighted sound levels can be measured with simple sound level meters. The ratings correlate well with human judgments of relative loudness but take no account of spectral balance or sound quality. Thus, many different-sounding spectra can result in the same numeric value, but have quite different subjective qualities.

The C-weighted sound level, denoted as dBC, is more sensitive to low-frequency sound contributions to the overall sound level than is dBA. A significant difference in the quantity (dBC – dBA) indicates that significant low-frequency sound is present.

NCB: Balanced Noise Criteria Method. The NCB method (ANSI *Standard* S12.2; Beranek 1989) is used to specify or evaluate room noise, including that from occupant activities. The NCB criterion curves (Figure 30) are intended as an improvement over the NC curves by including the two low-frequency octave bands (16 and 31.5 Hz), and by lowering permissible noise levels at high frequencies (4000 and 8000 Hz). Rating is based on the speech interference level (SIL = the average of the four sound pressure levels at octave midband frequencies of 500, 1000, 2000, and 4000 Hz) with additional tests for rumble and hiss compliance. The rating is expressed as NCB followed by a number (e.g., NCB 40).

The NCB method is better than the NC method in determining whether a noise spectrum has an unbalanced shape sufficient to demand corrective action, and it addresses the issue of low-frequency noise. Rating is, however, more complicated than the familiar NC

tangency method. The NCB method can still be used as a tangency method; if so used, the point of tangency, which sets the rating, must be denoted.

The NCB method evaluates low-frequency (16 and 31.5 Hz) sound levels with respect to the potential for noise-induced vibration. The NCB curves indicate that very high-amplitude sound levels may be acceptable based on the limits of the criteria curves. The threshold of human hearing is high at low frequencies, and high-amplitude, low-frequency sound energy may be "felt" rather than heard. Building architectural and mechanical systems can be excited into vibration that produces unacceptable shaking, rattling, and reradiation of noise. Any time low-frequency sound levels exceed those indicated by the lower limit of zone A shown in Figure 30, great care should be exercised in interpreting the acceptability of the results.

RC Mark II: Room Criteria Method. Based on experience and ASHRAE-sponsored research (Broner 1994), the RC method was revised to the RC Mark II method (Blazier 1997). Like its predecessor, the RC Mark II method is intended for rating the sound performance of an HVAC system as a whole. The method is most useful as a diagnostic tool for analyzing noise problems in the field. The RC Mark II method is more complicated to use than the RC method, but computerized spreadsheets and HVAC system analysis programs are available to perform the calculations and graphical analysis.

The RC Mark II method has three parts: (1) a family of criterion curves (Figure 31), (2) a procedure for determining the RC numerical rating and the noise spectral balance (quality), and (3) a procedure for estimating occupant satisfaction when the spectrum does

not have the shape of an RC curve (Quality Assessment Index) (Blazier 1995). The rating is expressed as RC followed by a number and a letter [e.g., RC 35(N)]. The number is the arithmetic average rounded to the nearest integer of the sound pressure levels in the 500, 1000, and 2000 Hz octave bands (the principal speech frequency region) and is known as the preferred speech interference level (PSIL). The letter is a qualitative descriptor that identifies the perceived character of the sound: (N) for neutral, (LF) for low-frequency rumble, (MF) for midfrequency roar, and (HF) for high-frequency hiss. There are also two subcategories of the low-frequency descriptor: (LF$_B$), denoting a moderate but perceptible degree of sound-induced ceiling/wall vibration, and (LF$_A$), denoting a noticeable degree of sound-induced vibration.

Each reference curve in Figure 31 identifies the shape of a neutral, bland-sounding spectrum, indexed to a curve number corresponding to the sound level in the 1000 Hz octave band. The shape of these curves is based on Blazier (1981a, 1981b), modified at 16 Hz following recommendations of the research in Broner (1994). Regions A and B denote levels at which sound can induce vibration in light wall and ceiling construction, which can potentially cause rattles in light fixtures, furniture, etc. Curve T is the octave band threshold of hearing as defined by ANSI *Standard* 12.2.

Procedure for Determining the RC Mark II Rating for a System.

Step 1. Obtain the arithmetic average of the sound levels in the principal speech frequency range represented by the levels in the 500, 1000, and 2000 Hz octave bands [preferred speech interference level (PSIL)]. [This is not to be confused with the ANSI-defined "speech-interference level" (SIL), a four-band average obtained by including the 4000 Hz octave band as used with the NCB method.] The RC reference curve is chosen to be that which has the same value at 1000 Hz as the calculated average value.

Step 2. Calculate the quality assessment index (QAI) (Blazier 1995), which measures the deviation of the spectrum under evaluation from the shape of the RC reference curve. Calculate the *energy-averaged* spectral deviations from the RC reference curve in each of three frequency groups: low (LF; 16 to 63 Hz), medium (MF; 125 to 500 Hz), and high (HF; 1000 to 4000 Hz). (A simple arithmetic average of these deviations is often adequate for most engineering purposes.) Equation (28) gives the procedure for the LF region; repeat for the MF and HF regions by substituting the corresponding values at each frequency.

$$\text{LF} = 10 \log \left[\left(10^{0.1 \Delta L_{16}} + 10^{0.1 \Delta L_{31.5}} + 10^{0.1 \Delta L_{63}} \right) / 3 \right] \quad (28)$$

The ΔL terms are the differences between the spectrum being evaluated and the RC reference curve in each frequency band. In this way, three specific spectral deviation factors, expressed in dB with either positive or negative values, are associated with the spectrum being rated. QAI is the *range* in dB between the highest and lowest values of the spectral deviation factors.

If QAI ≤ 5 dB, the spectrum is assigned a *neutral* (N) rating. If QAI *exceeds* 5 dB, the sound quality descriptor of the RC rating is the letter designation of the frequency region of the deviation factor having the highest *positive* value.

Example 7. The spectrum plotted in Figure 31 indicated by large dots is processed in Table 41.

The arithmetic average of the sound levels in the 500, 1000, and 2000 Hz octave bands is 35 dB, so the RC 35 curve is selected as the reference for spectrum quality evaluation.

The spectral deviation factors in the LF, MF, and HF regions are 6.6, 4.0, and –0.6 respectively, giving a QAI of 7.2. The maximum *positive* deviation factor occurs in the LF region and QAI exceeds 5; therefore, the rating of the spectrum is RC 35(LF). An average room occupant should perceive this spectrum as rumbly in character.

Table 41   Example 7 Calculation of RC Mark II Rating

	**Frequency, Hz**
	16	**31**	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**
Spectrum levels	64	65	64	57	47	40	35	30	23
Average of 500 to 2000 Hz levels							35		
RC contour	60	60	55	50	45	40	35	30	25
Levels—RC contour	4	5	9	7	2	0	0	0	–2
		LF			MF			HF	
Spectral deviations		6.6			4.0			–0.6	
QAI					7.2				
RC Mark II rating					**RC 35(LF)**				

Estimating Occupant Satisfaction Using QAI. The QAI estimates the probable reaction of an occupant when system design does not produce optimum sound quality. The basis for estimating occupant satisfaction is that changes in sound level of less than 5 dB do not cause subjects to change their ranking of sounds of similar spectral content. However, level changes greater than 5 dB do significantly affect subjective judgments. A QAI of 5 dB or less corresponds to a generally acceptable condition, provided that the perceived level of the sound is in a range consistent with the given type of space occupancy as recommended in Table 42. (An exception to this rule occurs when sound pressure levels in the 16 or 31 Hz octave bands exceed 65 dB. In such cases, there is potential for acoustically induced vibration in typical lightweight office construction. Levels above 75 dB in these bands indicate a significant problem with induced vibration.)

A QAI that exceeds 5 dB but is less than or equal to 10 dB represents a marginal situation, in which acceptance by an occupant is questionable. However, a QAI greater than 10 dB will likely be objectionable to the average occupant. Table 43 lists sound quality descriptors and QAI values and relates them to probable occupant reaction to the noise.

The numerical part of the RC rating may sometimes be less than the specified maximum for the space use, but with a sound quality descriptor other than the desirable (N). For example, a maximum of RC 40(N) is specified, but the actual noise environment turns out to be RC 35(MF). There is insufficient knowledge in this area to decide which spectrum is preferable.

Even at moderate levels, if the dominant portion of the background noise occurs in the very low-frequency region, some people can experience a sense of oppressiveness or depression in the environment (Perrson-Waye et al. 1997). Such a complaint may result after exposure to that environment for several hours, and thus may not be noticeable during a short exposure period.

Design Guidelines for HVAC-Related Background Sound in Rooms. Table 42 lists design guidelines for HVAC-related background sound appropriate to various types of space occupancies. Perceived loudness and task interference are factored into the numerical part of the RC rating. The sound-quality design target is assumed to be a neutral-sounding (N) spectrum, although some spectrum imbalance is probably tolerable within limits.

When taking field measurements to determine whether a space complies with the guidelines presented in Table 42, the following precautions must be taken:

• Measure the noise with an integrating sound level meter with a real-time frequency analyzer meeting type 1 or 2 specifications, as defined in ANSI *Standards* S1.4, S1.11, and S1.43. The meter should have been calibrated by an accredited calibration laboratory, with some assurance that the calibration accuracy has been maintained.

Table 42 Design Guidelines for HVAC-Related Background Sound in Rooms

Room Types	RC(N) (QAI ≤ 5 dB[a,b])	Room Types	RC(N) (QAI ≤ 5 dB[a,b])
Residences, Apartments, Condominiums	25 to 35	**Performing Arts Spaces**	
Hotels/Motels		Drama theaters, concert and recital halls	25
Individual rooms or suites	25 to 35	Music teaching studios	25
Meeting/banquet rooms	25 to 35	Music practice rooms	30 to 35
Corridors, lobbies	35 to 45	**Laboratories (with fume hoods)**	
Service/support areas	35 to 45	Testing/research, minimal speech communication	45 to 55
Office Buildings		Research, extensive telephone use, speech communication	40 to 50
Executive and private offices	25 to 35		
Conference rooms	25 to 35	Group teaching	35 to 45
Teleconference rooms	≤25	**Church, Mosque, Synagogue**	
Open-plan offices	≤40	General assembly with critical music programs[c]	25 to 35
With sound masking	≤35	**Schools[d]**	
Corridors and lobbies	40 to 45	Classrooms	25 to 30
Hospitals and Clinics		Large lecture rooms	25 to 30
Private rooms	25 to 35	Without speech amplification	≤25
Wards	30 to 40	**Libraries**	30 to 40
Operating rooms	25 to 35	**Indoor Stadiums, Gymnasiums**	
Corridors and public areas	30 to 40	Gymnasiums and natatoriums[e]	40 to 50
Courtrooms		Large seating-capacity spaces with speech amplification[e]	45 to 55
Unamplified speech	25 to 35		
Amplified speech	30 to 40		

[a]Values and ranges are based on judgment and experience, not on quantitative evaluations of human reactions. They represent general limits of acceptability for typical building occupancies. Higher or lower values may be appropriate and should be based on careful analysis of economics, space use, and user needs.

[b]When sound quality in the space is important, specify criteria in terms of RC(N). If sound quality in the space is of secondary concern, the criteria may be specified in terms of NC or NCB levels of similar magnitude.

[c]An experienced acoustical consultant should be retained for guidance on acoustically critical spaces (below RC 30) and for all performing arts spaces.

[d]Some educators and others believe that HVAC-related sound criteria for schools, as listed in previous editions of this table, are too high and impede learning for affected groups of all ages. See ANSI *Standard* S12.60-2002 for classroom acoustics and a justification for lower sound criteria in schools. The HVAC component of total noise meets the background noise requirement of that standard if HVAC-related background sound ≤ RC 25(N).

[e]RC or NC criteria for these spaces need only be selected for the desired speech and hearing conditions.

Table 43 Definition of Sound-Quality Descriptor and Quality-Assessment Index (QAI), to Aid in Interpreting RC Mark II Ratings of HVAC-Related Sound

Sound-Quality Descriptor	Description of Subjective Perception	Magnitude of QAI	Probable Occupant Evaluation, Assuming Level of Specified Criterion is Not Exceeded
(N) Neutral (Bland)	Balanced sound spectrum, no single frequency range dominant	QAI ≤ 5 dB, L_{16}, L_{31} ≤ 65	Acceptable
		QAI ≤ 5 dB, L_{16}, L_{31} > 65	Marginal
(LF) Rumble	Low-frequency range dominant (16 to 63 Hz)	5 dB < QAI ≤ 10 dB	Marginal
		QAI > 10 dB	Objectionable
(LFV$_B$) Rumble, with moderately perceptible room surface vibration	Low-frequency range dominant (16 to 63 Hz)	QAI ≤ 5 dB, 65 < L_{16}, L_{31} < 75	Marginal
		5 dB < QAI ≤ 10 dB	Marginal
		QAI > 10 dB	Objectionable
(LFV$_A$) Rumble, with clearly perceptible room surface vibration	Low-frequency range dominant (16 to 63 Hz)	QAI ≤ 5 dB, L_{16}, L_{31} > 75	Marginal
		5 dB < QAI ≤ 10 dB	Marginal
		QAI > 10 dB	Objectionable
(MF) Roar	Mid-frequency range dominant (125 to 500 Hz)	5 dB < QAI ≤ 10 dB	Marginal
		QAI > 10 dB	Objectionable
(HF) Hiss	High-frequency range dominant (1000 to 4000 Hz)	5 dB < QAI ≤ 10 dB	Marginal
		QAI > 10 dB	Objectionable

Table 44 Plumbing Noise Levels

Receiving (listening) room	L_{max} (slow response)
Residential bedroom/living room/dining room	35
Hospital patient room/classroom	40
Private office/conference room	40
Residential bathroom/kitchen	45
Open office/lobby/corridor	50

- Set the meter to display and save the equivalent energy sound pressure level (L_{eq}) with the desired frequency filtering (e.g., octave bands, A-weighted, etc.). Each measurement should be 15 s long.
- Place the measurement microphone in potential listening locations at least 3.2 ft from room boundaries and noise sources and

at least 1.6 ft from furniture. More than one location may be measured, and the microphone may be moved during measurement; movement should not exceed 6 in/s.

- Note the operational conditions of the HVAC system at the time of the test. Turn off all non-HVAC system noises during the test. If possible, measure in a normally furnished, unoccupied room.
- The test may be repeated with the entire HVAC system turned off, to determine whether the room's ambient noise level from non-HVAC sources is contaminating the results.
- Record the sound level meter make, model, and serial number, the measured sound pressure levels, the HVAC system's operating conditions, and the microphone location(s).

When these levels are used as a basis for compliance verification, the following additional information must be provided:

- What sound metrics are to be measured (specify L_{eq} or L_{max} levels, etc., in each octave frequency band)
- Where and how the sound levels are to be measured (specify the space average over a defined area or specific points for a specified minimum time duration, etc.)
- What type(s) of instruments are to be used to make the sound measurements (specify ANSI or IEC Type 1 or Type 2 sound level meters with octave band filters, etc.)
- How sound measurements instruments are to be calibrated or checked (specify that instruments are to be checked with an acoustical calibrator both before and after taking sound level measurements, etc.)
- How sound level measurements are to be adjusted for the presence of other sound sources (specify that background sound level measurements be performed without other sound sources under consideration operating; if background sound levels are within 10 dB of operational sound levels, then corrections should be performed; etc.)
- How results of sound measurements are to be interpreted (specify whether octave band sound levels, NC, RC, dBA, or other values are to be reported)

Unless these six points are clearly stipulated, the specified sound criteria may be unenforceable.

When applying the levels specified in Table 42 as a basis for design, sound from non-HVAC sources, such as traffic and office equipment, may establish the lower limit for sound levels in a space.

Noise Criteria for Plumbing Systems. Acceptable noise levels from plumbing fixtures and piping have not been previously identified in the literature. Continuous noise from plumbing fixtures and piping systems with circulating fluids could meet the same noise criteria as HVAC systems. However, many sounds from plumbing fixtures and piping are of short duration or are transient, and typically have a somewhat higher threshold of acceptance. Examples of these sources include water flow noise associated with typical restroom fixtures; noise from waste lines connected to restroom, kitchen, and/or laundry drains; and noise from jetted bathtubs. The following table presents suggested maximum A-weighted sound pressure levels for various transient plumbing noise sources in buildings with multiple occupancies. These criteria are minimum standards and are intended to apply to plumbing systems serving adjacent and nearby units in multifamily housing projects (apartments and condominiums), hospitals, educational facilities, and office buildings. Plumbing noise levels in high-end luxury condominiums should be 5 to 10 dB lower than levels shown in Table 44.

Achieving the recommended plumbing noise criteria in the finished space will usually require special attention to pipe installation details, selection of suitable piping materials, and selection of appropriate fixtures.

Outdoor Sound Criteria

Acceptable outdoor sound levels are generally specified by local noise ordinances, which almost always use the A-weighted noise level (dBA) as their metric. The usual metric is either L_{max} (maximum noise level over a period), L_{eq} (average noise level over a period), or L_p (no indication of the measure). The time constant used for L_{max} or L_p depends on the community code. Some communities have no ordinance and depend on state regulations. These often use the day-night noise level descriptor L_{DN}, a combination of the daytime (7:00 AM to 10:00 PM) and nighttime (10:00 PM to 7:00 AM) average noise levels (L_{eq}) with a 10 dB penalty for nighttime (Cowan 1994; Schultz 1972).

Measurement or estimation of community noise is based on a location, often at the receiver's property line, from a height of approximately 4 ft to any height, but can be anywhere within the property line, and often near the facade of the closest dwelling unit.

Alternatively, the measurement may be made at the property line of the noise source.

In the absence of a local noise ordinance, county or state laws or codes or those of a similar community should be used. Even if activity noise levels do not exceed those specified by an ordinance, community acceptance is not ensured. Very low ambient levels or a noise source with an often-repeated time-varying characteristic may increase the likelihood of complaints.

Although most ordinances are given as A-weighted pressure level, attenuation by distance, barriers, buildings, and atmosphere are all frequency-dependent. Thus, A-weighted levels do not give an accurate estimation of noise levels at distances from the source. If A-weighted sound levels of sources must be determined by means other than measurement, then octave band or one-third octave band measurements of source sound pressure level at a distance, or (preferably) sound power level, must be obtained before calculating the attenuation.

HVAC NOISE REDUCTION DESIGN PROCEDURES

These HVAC system design procedures address the 63 to 4000 Hz octave band midfrequency range. Although it is desirable to extend this frequency range down into the 31.5 Hz octave band, acoustical calculations below the 125 Hz octave band are not reliable. With a few exceptions, if acoustical design criteria are met at 4000 Hz, then the 8000 Hz requirements are also met. Guidelines in this chapter and other guides maximize the probability of meeting acoustical design criteria in the 31.5 to 8000 Hz octave bands.

There is reasonable probability that the acoustical design criteria will be met when the following requirements are satisfied:

- Systems are designed in accordance with the equipment selection, placement, and integration guidelines in this chapter, other ASHRAE guides, and manufacturers' application notes and bulletins.
- Acoustical calculations based on the information included in this chapter and the information provided by the equipment manufacturer indicate that the system will not exceed the selected acoustical design criteria values in the 63 to 4000 Hz octave band frequency range.

The following suggested design procedure uses the NC method, which is the most commonly used. Other criteria, such as NCB or RC, may be used. However, it is often difficult to acquire low-frequency sound data, and low-frequency acoustical calculations for HVAC system components are not reliable.

1. Determine the design goal for HVAC system noise for each critical area according to its use and construction. Choose the desirable NC criterion from Table 42, assuming that the RC(N) listed are comparable to the NC.
2. Select equipment and fittings (e.g., air inlet and outlet grilles, registers, diffusers, and air terminal and fan-coil units that radiate sound directly into a room) that will be quiet enough to meet design goals.
3. Complete initial design and layout of the HVAC system. Include typical duct lining where appropriate. Provide space for duct sound attenuators.
4. Calculate sound pressure level in the room of interest:
   (a) Acquire sound power data from manufacturers for equipment such as air-handling units, packaged rooftop units, exhaust fans, variable-air-volume terminal units, fan-powered terminal units, etc. If manufacturers' data are not available, estimate sound power level based on methods in this chapter or other authoritative sources.
   (b) Calculate sound attenuation and regenerated sound power of duct elements in the air distribution system of interest.
   (c) Tabulate sound power and attenuation for each component in each sound transmission path. Start at the supply air fan or packaged air-conditioning unit and end at the room.

Investigate both the supply and return air paths in similar ways. Investigate possible duct sound breakout when fans are adjacent to, or roof-mounted fans are above, the room of interest. Combine sound power levels from all paths. See Example 8 for calculation procedures for supply and return air paths, including duct breakout noise contributions. Include a placeholder for the duct sound attenuator so that it is a simple matter to include in calculations later.

    (d) Convert sound power levels to corresponding sound pressure levels in the room.

5. If the mechanical equipment room is adjacent to the room of interest, determine sound pressure levels in the room of interest that are associated with sound transmitted through the mechanical equipment room wall. Air-handling units, ventilation and exhaust fans, chillers, pumps, electrical transformers, and instrument air compressors are typical equipment to consider. Also consider the vibration isolation requirements for equipment, piping, and ductwork. [See Egan (1988) or Reynolds and Bledsoe (1991) for calculation procedure.]

6. Combine on an energy basis the sound pressure levels in the room of interest that are associated with all sound paths between the mechanical equipment room or roof-mounted unit(s) and the room of interest.

7. Determine the corresponding NC level associated with the calculated total sound pressure levels in the room of interest. Take special note of unbalanced sound spectra and tonal characteristics.

8. If the NC level satisfies the criteria established in Step 1, analysis is complete. If the NC level exceeds the design goal, determine the octave frequency bands in which the corresponding sound pressure levels are exceeded and the sound paths associated with these octave frequency bands. If the resulting noise levels are high enough to cause perceivable vibration, consider both airborne and structureborne noise.

9. Redesign the system:

    (a) Reselect the offending noise source. This is typically the least costly, most energy-efficient, and most effective change, but is not always possible.

    (b) Add sound attenuation to paths that contribute to excessive sound pressure levels in the room of interest.

    (c) If resultant noise levels are high enough to cause perceivable vibration, then major redesign and possibly use of supplemental vibration isolation for equipment and building systems are often required.

10. Repeat Steps 4 through 9 until the desired design goal is achieved. Involve the complete design team where major problems are found. Often, simple design changes to building architectural and equipment selection can eliminate potential problems once the problems are identified.

11. Repeat Steps 3 through 10 for every room that is to be analyzed.

12. Make sure that noise radiated by outdoor equipment such as air-cooled chillers and cooling towers does not disturb adjacent properties or interfere with criteria established in Step 1 or any applicable building or zoning noise ordinances.

Example 8. This example illustrates Step 4 in the design process. Previous examples demonstrate how to calculate equipment- and air distribution system airflow-generated sound power levels and attenuation values. Here, the individual elements are combined to determine sound pressure levels associated with a specific HVAC system. Only a summary of tabulated results is listed rather than showing complete calculations for each element. Calculations for each element are strictly based on the methods in this chapter or manufacturers' data.

    Air is supplied to the HVAC system by the rooftop unit shown in Figure 32. The receiver room is directly below the unit. The room has the following dimensions: length = 20 ft, width = 20 ft, and height = 9 ft. Assume that the roof penetrations for supply and return air ducts are well sealed and there are no other roof penetrations. The supply side of
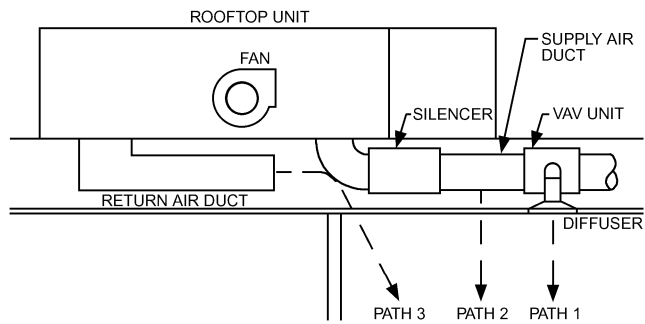
Fig. 32 Sound Paths Layout for Example 8
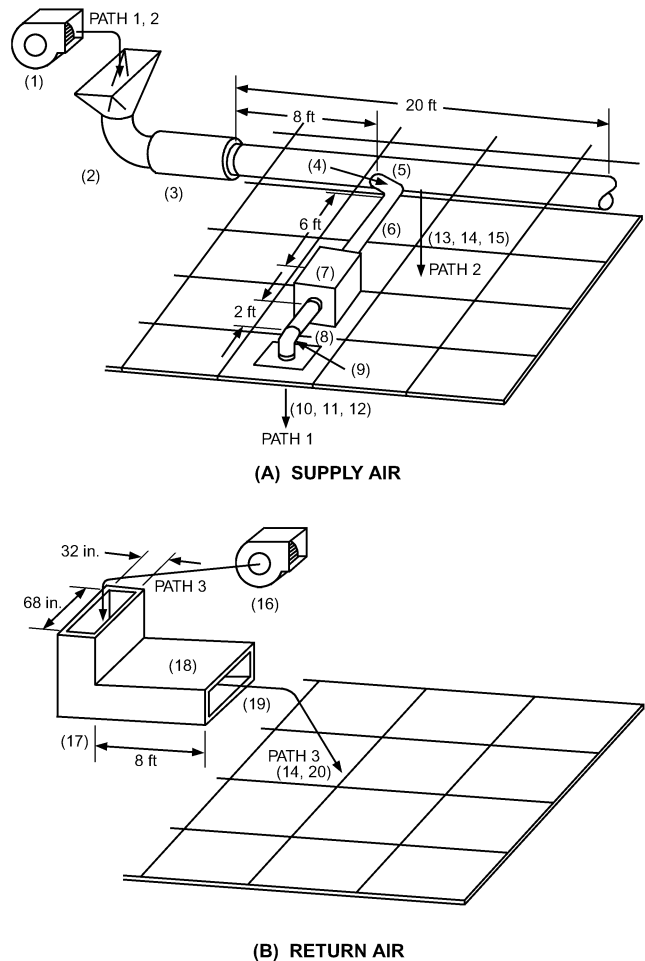
Fig. 33 (A) Supply and (B) Return Air Layout for Example 8

the rooftop unit is ducted to a VAV terminal control unit serving the room in question. A return air grille conducts air to a common ceiling return air plenum. The return air is then directed to the rooftop unit through a short rectangular return air duct.

    The following three sound paths are to be examined:

Path 1. Fan airborne supply air sound that enters the room from the supply air system through the ceiling diffuser

Path 2. Fan airborne supply air sound that breaks out through the wall of the main supply air duct into the plenum space above the room

Path 3. Fan airborne return air sound that enters the room from the inlet of the return air duct

The tabulated calculations for each path follow:

Path 1

Element		Sound Power Attenuation, dB							Regenerated Sound Power, dB							Path Sound Power, dB						
ID	Description	63	125	250	500	1000	2000	4000	63	125	250	500	1000	2000	4000	63	125	250	500	1000	2000	4000
01	Supply air fan, 7000 cfm, 2.5 in. of water	0	0	0	0	0	0	0	92	86	80	78	78	74	71	92	86	80	78	78	74	71
02	22 in. dia., 90° rad. unlined elbow	0	1	2	3	3	3	3	0	0	0	0	0	0	0	92	85	78	75	75	71	68
03	22 × 44 in. long sound attenuator	4	7	19	31	38	38	27	68	79	69	60	59	59	55	88	82	69	60	59	59	55
04	22 in. dia., 8 ft long unlined duct	0	0	0	0	0	0	0	0	0	0	0	0	0	0	88	82	69	60	59	59	55
05.2	10 in. dia. branch, 22 in. dia. main, branch path	8	8	8	8	8	8	8	0	0	0	0	0	0	0	80	74	61	52	51	51	47
06	10 in. dia., 6 ft long unlined duct	0	0	0	0	0	0	0	0	0	0	0	0	0	0	80	74	61	52	51	51	47
07	VAV terminal	0	5	10	15	15	15	15	0	0	0	0	0	0	0	80	69	51	37	36	36	32
08	10 in. dia., 2 ft long unlined duct	0	0	0	0	0	0	0	0	0	0	0	0	0	0	80	69	51	37	36	36	32
09	10 in. dia., 90° rad. unlined elbow	0	0	1	2	3	3	3	0	0	0	0	0	0	0	80	69	50	35	33	33	29
10	10 in. dia. diffuser end reflection	14	9	5	2	1	0	0	0	0	0	0	0	0	0	66	60	45	33	32	33	29
11	15 × 15 in. rectangular diffuser	0	0	0	0	0	0	0	31	36	39	40	39	36	30	66	60	46	41	40	38	33
12	ASHRAE room correction: point source	3	4	5	6	7	8	9	0	0	0	0	0	0	0	63	56	41	35	33	30	24

Path 2

Element		Sound Power Attenuation, dB							Regenerated Sound Power, dB							Path Sound Power, dB						
ID	Description	63	125	250	500	1000	2000	4000	63	125	250	500	1000	2000	4000	63	125	250	500	1000	2000	4000
01	Supply air fan, 7000 cfm, 2.5 in. of water	0	0	0	0	0	0	0	92	86	80	78	78	74	71	92	86	80	78	78	74	71
02	22 in. dia., 90° rad. unlined elbow	0	1	2	3	3	3	3	0	0	0	0	0	0	0	92	85	78	75	75	71	68
03	22 × 44 in. long sound attenuator	4	7	19	31	38	38	27	68	79	69	60	59	59	55	88	82	69	60	59	59	55
04	22 in. dia., 8 ft long unlined duct	0	0	0	0	0	0	0	0	0	0	0	0	0	0	88	82	69	60	59	59	55
05.1	10 in. dia. branch, 22 in. dia. main, main path	1	1	1	1	1	1	1	0	0	0	0	0	0	0	87	81	68	59	58	58	54
13	22 in. dia., 20 ft long 24 ga. duct breakout	35	37	35	28	20	10	13	0	0	0	0	0	0	0	52	44	34	32	38	48	42
14	2 ft × 4 ft × 5/8 in. lay-in ceiling	13	15	17	19	25	30	33	0	0	0	0	0	0	0	39	29	17	13	13	18	9
15	ASHRAE room correction: line source	15	15	15	15	15	15	15	0	0	0	0	0	0	0	24	14	2	0	0	3	0

Path 3

Element		Sound Power Attenuation, dB							Regenerated Sound Power, dB							Path Sound Power, dB						
ID	Description	63	125	250	500	1000	2000	4000	63	125	250	500	1000	2000	4000	63	125	250	500	1000	2000	4000
16	Return air fan, 7000 cfm, 2.5 in. of water	0	0	0	0	0	0	0	82	79	80	78	78	74	71	82	79	80	78	78	74	71
17	32 × 68 in., 90° mitered unlined elbow	1	5	8	4	3	3	3	0	0	0	0	0	0	0	81	74	72	74	75	71	68
18	32 × 68 in., 8 ft long lined duct	0	1	2	8	16	10	10	0	0	0	0	0	0	0	81	73	70	66	59	61	58
19	32 × 68 in. end reflection loss	4	1	0	0	0	0	0	0	0	0	0	0	0	0	77	72	70	66	59	61	58
14	2 ft × 4 ft × 5/8 in. lay-in ceiling	13	15	17	19	25	30	33	0	0	0	0	0	0	0	64	57	53	47	34	31	25
20	ASHRAE room correction: point source	3	4	5	6	7	8	9	0	0	0	0	0	0	0	61	53	48	41	27	23	16

Receiver Room Summary

Path Description: Rooftop Unit to	Path Sound Pressure Level, dB							
	63	125	250	500	1000	2000	4000	NC
1 Ceiling diffuser	63	56	41	35	33	30	24	39
2 Duct breakout	24	14	2	0	0	3	0	0
3 Return air	61	53	48	41	27	23	16	36
	65	57	49	42	34	31	24	42

Fig. 34   NC Rating Calculated

Calculation Procedure

Analysis for each path begins at the rooftop unit and proceeds through the different system elements to the receiver room. The element numbers in the tables correspond to those in Figure 33. The source of each element calculation is listed in Table 45. Sound data for the rooftop unit (supply and return openings), VAV terminal, diffuser, and duct sound attenuator are manufacturers' data.

A spreadsheet was used to perform the calculations associated with this example. This type of calculation is often performed iteratively, as described in the preceding design procedure, but using a well-crafted spreadsheet increases the speed and accuracy of calculations.

Calculation tables for paths 1, 2, and 3 are organized with an element in each row. Three spectra (63 Hz to 4000 Hz) are shown for each element. The first and second spectra (sound power attenuation and regenerated sound power) are either calculated based on the equations and tables in this chapter or acquired from a manufacturer. It is important to note that sound power data and not sound pressure data must be used in these calculations.

The spreadsheet subtracts the sound attenuation spectrum, band by band, from the path sound power spectrum in the previous row. Then, the resultant sound power is logarithmically added per band to the element sound power. This calculation is performed for each element (row).

$$L_w = 10\log\left(10^{L_{w1}/10} + 10^{L_{w2}/20}\right) \qquad (29)$$

The last element in each path is the ASHRAE room sound correction, which is entered as an attenuation spectrum as it is subtracted directly from the final path sound power spectrum. These are then summarized in the last calculation table and logarithmically added using Equation (29). The NC value for this spectrum is calculated using methods described in this chapter (see Figure 34).

Table 45   Path Element Sound Calculation Reference

ID	Description	Data Source Reference
01	Supply air fan, 7000 cfm, 2.5 in. of water	Manufacturer's data
02	22 in. dia., 90° rad. unlined elbow	Attenuation: Table 18
03	22 × 44 in. long sound attenuator	Manufacturer's data
04	22 in. dia., 8 ft long unlined duct	Attenuation: Table 11
05.2	10 in. dia. branch, 22 in. dia. main, branch path	Attenuation: Table 22
05.1	10 in. dia. branch, 22 in. dia. main, main path	Attenuation: Table 22
06	10 in. dia., 6 ft long unlined duct	Attenuation: Table 11
07	VAV terminal	Manufacturer's data
08	10 in. dia., 2 ft long unlined duct	Attenuation: Table 11
09	10 in. dia., 90° rad. unlined elbow	Attenuation: Table 18
10	10 in. dia. diffuser, end reflection	Attenuation: Table 24
11	15 × 15 in. rectangular diffuser	Manufacturer's data
12	ASHRAE room correction: point source	Equation (22), Tables 32 and 33
13	22 in. dia., 20 ft long, 24 ga. duct breakout	Attenuation: Equation (9), Table 26
14	2 × 4 ft × 5/8 in. lay-in ceiling	Attenuation: Table 28
15	ASHRAE room correction: line source	Equation (25)
16	Return air fan, 7000 cfm, 2.5 in. of water	Manufacturer's data
17	32 × 68 in., 90° mitered unlined elbow	Attenuation: Tables 17 and 19
18	32 × 68 in., 8 ft long lined duct	Attenuation: Table 12, $P = 200$ in.; assume 0 dB at 63 Hz
19	32 × 68 in. end reflection loss	Attenuation: Table 23, $D = 43.5$ in.
20	ASHRAE room correction: point source	Equation (22), Tables 32 and 33

HEALTH EFFECTS OF ACOUSTICAL MATERIALS

For information on possible health effects of some materials (e.g., fiberglass), please see the International Agency for Research on Cancer (IARC; www.iarc.fr) and the North American Insulation Manufacturers Association (NAIMA; www.naima.org/main.html).

VIBRATION ISOLATION AND CONTROL

Mechanical vibration and vibration-induced noise are often major sources of occupant complaints in modern buildings. Lightweight construction in new buildings increases susceptibility to vibration and related problems. Increased interest in energy conservation has resulted in many new buildings being designed with variable-air-volume systems. This often results in mechanical equipment being located in penthouses on the roof, in the use of roof-mounted HVAC units, and in locating mechanical equipment rooms on intermediate-level floors, with more mechanical equipment located in a building and/or adjacent to or above occupied areas.

Occupant complaints associated with building vibration typically take one or more of three forms:

• The level of vibration perceived by building occupants is of sufficient magnitude to cause concern or alarm
• Vibration energy from mechanical equipment, which is transmitted to the building structure, is transmitted to various parts of the building and then is radiated as structureborne noise
• Vibration in a building may interfere with proper operation of sensitive equipment or instrumentation

The following sections present basic information to properly select and specify vibration isolators and to analyze and correct field vibration problems.
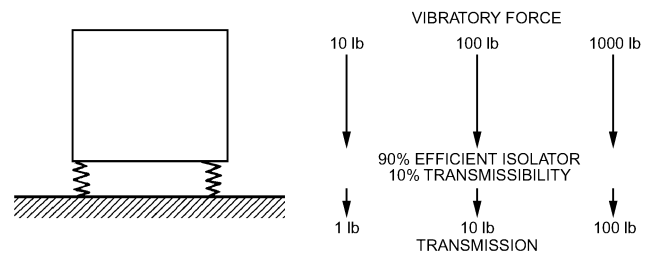
Fig. 35   Transmission to Structure Varies as Function of Magnitude of Vibration Force
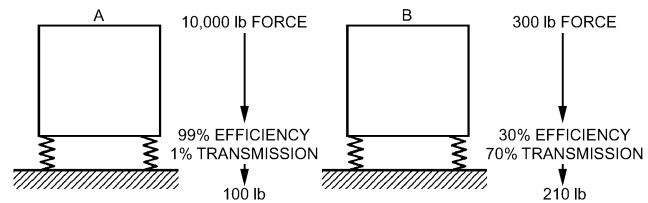
Fig. 36   Interrelationship of Equipment Vibration, Isolation Efficiency, and Transmission

EQUIPMENT VIBRATION

Any vibrating, reciprocating, or rotating equipment should be mounted such that it does not transmit significant levels of vibration into the surrounding or supporting structure. Vibrations transmitted via machine mounts or attached piping, ductwork, or electrical connections can result in vibrating walls, floors, and/or ceilings, which in turn radiate sound and/or vibration. Hence, it is important to provide vibration isolation for all attachments to a vibrating machine, including structural mounts, cooling or drainage pipe connections, exhaust air ductwork, and electrical connections, among others.

Vibration can be isolated or reduced to a fraction of the original force with resilient mounts between the equipment and the supporting structure, provided that the supporting structure has sufficient stiffness and mass. **Isolation efficiency** is the percentage of vibratory force *not* transmitted to the support structure. Figure 35 shows that 90% efficiency results in 10% of the vibration force being transmitted. In this case, the magnitude of transmission to the building is a function of the magnitude of the vibration force. Figure 36 shows the effect of different efficiency levels.

VIBRATION CRITERIA

For the HVAC designer, vibration criteria are specified relative to three areas: (1) human response to vibration, (2) vibration levels associated with potential disruption to the use of sensitive equipment in a building, and (3) vibration severity of an operating machine. Figure 37 and Table 46 present recommended acceptable criteria for vibration in a building structure (IEST 2005; Murray et al. 1997). The vibration values in Figure 37 are measured in one-third octave bands using vibration transducers (usually accelerometers) placed on the building structure near vibrating equipment or in areas containing occupants or sensitive equipment. Occupant vibration criteria are based on guidelines recommended in ANSI *Standard* S3.29 and ISO *Standard* 2631-2. For sensitive equipment, acceptable vibration values specified by equipment manufacturers should be used. If none are available, then criteria from IEST (2005), as reflected in Figure 37 and Table 46, can be used.

If acceptable vibration values are not available from equipment manufacturers, the values specified in Figure 38 can be used. This figure gives recommended equipment vibration severity ratings based on measured RMS velocity values (IRD 1988). The vibration values in Figure 38 are measured by vibration transducers (usually
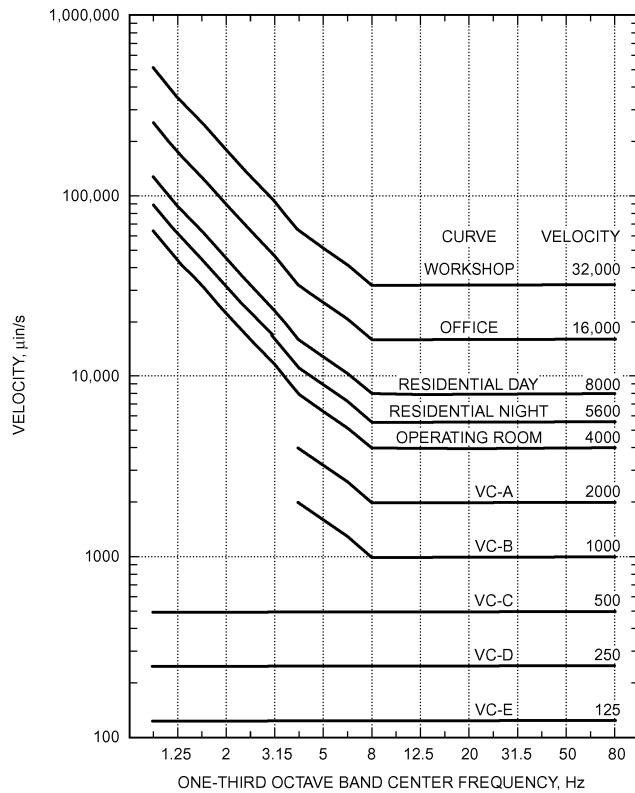
Fig. 37 Building Vibration Criteria for Vibration Measured on Building Structure
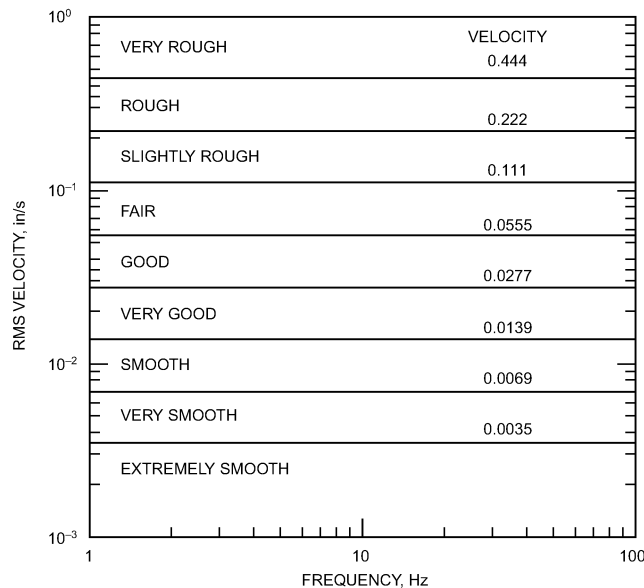
Fig. 38 Equipment Vibration Severity Rating for Vibration Measured on Equipment Structure or Bearing Caps

accelerometers) mounted directly on equipment, equipment structures, or bearing caps. Vibration levels measured on equipment and components can be affected by equipment unbalance, misalignment of equipment components, and resonance interaction between a vibrating piece of equipment and the floor on which it is placed. If a piece of equipment is balanced within acceptable tolerances and excessive vibration levels still exist, the equipment and installation should be checked for possible resonant conditions Table 47 gives

Table 46 Human Comfort and Equipment Vibration Criteria

Human Comfort	Time of Day	8 to 80 Hz Curve,[a] μin/s
Workshops	All	32,000
Office areas	All[b]	16,000
Residential (good environmental standards)	0700-2200[b]	8000
	2200-0700[b]	5600
Hospital operating rooms and critical work areas	All	4000
Equipment Requirements		**Curve[a]**
Adequate for computer equipment, probe test equipment, and microscopes less than 40×		8000
Bench microscopes up to 100× magnification; laboratory robots		4000
Bench microscopes up to 400× magnification; optical and other precision balances; coordinate measuring machines; metrology laboratories; optical comparators; microelectronics manufacturing equipment; proximity and projection aligners, etc.		2000
Microsurgery, eye surgery, neurosurgery; bench microscopes at magnification greater than 400×; optical equipment on isolation tables; microelectronic manufacturing equipment, such as inspection and lithography equipment (including steppers) to 3 mm line widths[c]		1000
Electron microscopes up to 30,000× magnification; microtomes; magnetic resonance imagers; microelectronics manufacturing equipment, such as lithography and inspection equipment to 1 mm detail size[c]		500
Electron microscopes at magnification greater than 30,000×; mass spectrometers; cell implant equipment; microelectronics manufacturing equipment, such as aligners, steppers, and other critical equipment for photolithography with line widths of 1/2 μm; includes electron beam systems[c]		250
Unisolated laser and optical research systems; microelectronics manufacturing equipment, such as aligners, steppers, and other critical equipment for photolithography with line widths of 1/4 μm; includes electron beam systems[c]		125

[a]See Figure 37 for corresponding curves.
[b]In areas where individuals are sensitive to vibration, use Residential Day curve.
[c]Classes of microelectronics manufacturing equipment:

Table 47 Maximum Allowable RMS Velocity Levels

Equipment	Allowable rms Velocity, in/s
Pumps	0.13
Centrifugal compressors	0.13
Fans (vent sets, centrifugal, axial)	0.09

maximum allowable RMS velocity levels for selected pieces of equipment.

Vibration levels measured on equipment structures should be in or below the "Good" region in Figure 38. Machine vibration levels in the "Fair" or "Slightly Rough" regions may indicate potential problems requiring maintenance. Machines with vibration levels in these regions should be monitored to ensure problems do not arise. Machine vibration levels in the "Rough" and "Very Rough" regions indicate a potentially serious problem; immediate action should be taken to identify and correct the problem.

SPECIFICATION OF VIBRATION ISOLATORS

Vibration isolators must be selected not only to provide required isolation efficiency but also to compensate for floor stiffness. Longer floor spans are more flexible and thus more easily set into vibration. Floor spans, equipment operating speeds, equipment power, damping, and other factors are considered in Table 48.

Table 48   Selection Guide for Vibration Isolation

Equipment Type	Horsepower and Other	RPM	Slab on Grade Base Type	Slab on Grade Isolator Type	Slab on Grade Min. Defl., in.	Up to 20 ft Base Type	Up to 20 ft Isolator Type	Up to 20 ft Min. Defl., in.	20 to 30 ft Base Type	20 to 30 ft Isolator Type	20 to 30 ft Min. Defl., in.	30 to 40 ft Base Type	30 to 40 ft Isolator Type	30 to 40 ft Min. Defl., in.	Reference Notes
Refrigeration Machines and Chillers															
Reciprocating	All	All	A	2	0.25	A	4	0.75	A	4	1.50	A	4	2.50	2,3,12
Centrifugal, screw	All	All	A	1	0.25	A	4	0.75	A	4	1.50	A	4	1.50	2,3,4,12
Open centrifugal	All	All	C	1	0.25	C	4	0.75	C	4	1.50	C	4	1.50	2,3,12
Absorption	All	All	A	1	0.25	A	4	0.75	A	4	1.50	A	4	1.50	
Air Compressors and Vacuum Pumps															
Tank-mounted horiz.	≤10	All	A	3	0.75	A	3	0.75	A	3	1.50	A	3	1.50	3,15
	≥15	All	C	3	0.75	C	3	0.75	C	3	1.50	C	3	1.50	3,15
Tank-mounted vert.	All	All	C	3	0.75	C	3	0.75	C	3	1.50	C	3	1.50	3,15
Base-mounted	All	All	C	3	0.75	C	3	0.75	C	3	1.50	C	3	1.50	3,14,15
Large reciprocating	All	All	C	3	0.75	C	3	0.75	C	3	1.50	C	3	1.50	3,14,15
Pumps															
Close-coupled	≤7.5	All	B	2	0.25	C	3	0.75	C	3	0.75	C	3	0.75	16
	≥10	All	C	3	0.75	C	3	0.75	C	3	1.50	C	3	1.50	16
Large inline	5 to 25	All	A	3	0.75	A	3	1.50	A	3	1.50	A	3	1.50	
	≥30	All	A	3	1.50	A	3	1.50	A	3	1.50	A	3	2.50	
End suction and split case	≤40	All	C	3	0.75	C	3	0.75	C	3	1.50	C	3	1.50	16
	50 to 125	All	C	3	0.75	C	3	0.75	C	3	1.50	C	3	2.50	10,16
	≥150	All	C	3	0.75	C	3	1.50	C	3	2.50	C	3	3.50	10,16
Cooling Towers	All	Up to 300	A	1	0.25	A	4	3.50	A	4	3.50	A	4	3.50	5,8,18
		301 to 500	A	1	0.25	A	4	2.50	A	4	2.50	A	4	2.50	5,18
		500 and up	A	1	0.25	A	4	0.75	A	4	0.75	A	4	1.50	5,18
Boilers (Fire-tube)	All	All	A	1	0.25	B	4	0.75	B	4	1.50	B	4	2.50	4
Axial Fans, Fan Heads, Cabinet Fans, Fan Sections															
Up to 22 in. diameter	All	All	A	2	0.25	A	3	0.75	A	3	0.75	C	3	0.75	4,9
24 in. diameter and up	≤2 in. SP	Up to 300	B	3	2.50	C	3	3.50	C	3	3.50	C	3	3.50	9
		300 to 500	B	3	0.75	B	3	1.50	C	3	2.50	C	3	2.50	9
		501 and up	B	3	0.75	B	3	1.50	B	3	1.50	B	3	1.50	9
	≥2.1 in. SP	Up to 300	C	3	2.50	C	3	3.50	C	3	3.50	C	3	3.50	3,9
		300 to 500	C	3	1.50	C	3	1.50	C	3	2.50	C	3	2.50	3,8,9
		501 and up	C	3	0.75	C	3	1.50	C	3	1.50	C	3	2.50	3,8,9
Centrifugal Fans															
Up to 22 in. diameter	All	All	B	2	0.25	B	3	0.75	B	3	0.75	C	3	1.50	9,19
24 in. diameter and up	≤40	Up to 300	B	3	2.50	B	3	3.50	B	3	3.50	B	3	3.50	8,19
		300 to 500	B	3	1.50	B	3	1.50	B	3	2.50	B	3	2.50	8,19
		501 and up	B	3	0.75	B	3	0.75	B	3	0.75	B	3	1.50	8,19
	≥50	Up to 300	C	3	2.50	C	3	3.50	C	3	3.50	C	3	3.50	2,3,8,9,19
		300 to 500	C	3	1.50	C	3	1.50	C	3	2.50	C	3	2.50	2,3,8,9,19
		501 and up	C	3	1.00	C	3	1.50	C	3	1.50	C	3	2.50	2,3,8,9,19
Propeller Fans															
Wall-mounted	All	All	A	1	0.25	A	1	0.25	A	1	0.25	A	1	0.25	
Roof-mounted	All	All	A	1	0.25	A	1	0.25	B	4	1.50	D	4	1.50	
Heat Pumps	All	All	A	3	0.75	A	3	0.75	A	3	0.75	A/D	3	1.50	
Condensing Units	All	All	A	1	0.25	A	4	0.75	A	4	1.50	A/D	4	1.50	
Packaged AH, AC, H and V Units															
All	10	All	A	3	0.75	A	3	0.75	A	3	0.75	A	3	0.75	19
	≤15 ≤4 in. SP	Up to 300	A	3	0.75	A	3	3.50	A	3	3.50	C	3	3.50	2,4,8,19
		301 to 500	A	3	0.75	A	3	2.50	A	3	2.50	A	3	2.50	4,19
		501 and up	A	3	0.75	A	3	1.50	A	3	1.50	A	3	1.50	4,19
	≤15, ≤4 in. SP	Up to 300	B	3	0.75	C	3	3.50	C	3	3.50	C	3	3.50	2,3,4,8,9
		301 to 500	B	3	0.75	C	3	1.50	C	3	2.50	C	3	2.50	2,3,4,9
		501 and up	B	3	0.75	C	3	1.50	C	3	1.50	C	3	2.50	2,3,4,9
Packaged Rooftop Equipment	All	All	A/D	1	0.25	D	3	0.75				See Reference Note No: 17			5,6,8,17
Ducted Rotating Equipment															
Small fans, fan-powered boxes	≤600 cfm	All	A	3	0.50	A	3	0.50	A	3	0.50	A	3	0.50	7
	≥601 cfm	All	A	3	0.75	A	3	0.75	A	3	0.75	A	3	0.75	7
Engine-Driven Generators	All	All	A	3	0.75	C	3	1.50	C	3	2.50	C	3	3.50	2,3,4

Base Types:
A. No base, isolators attached directly to equipment (Note 27)
B. Structural steel rails or base (Notes 28 and 29)
C. Concrete inertia base (Note 30)
D. Curb-mounted base (Note 31)

Isolator Types:
1. Pad, rubber, or glass fiber (Notes 20 and 21)
2. Rubber floor isolator or hanger (Notes 20 and 25)
3. Spring floor isolator or hanger (Notes 22, 23, and 25)
4. Restrained spring isolator (Notes 22 and 24)
5. Thrust restraint (Note 26)

Notes for Table 48: Selection Guide for Vibration Isolation

These notes are keyed to the column titled *Reference Notes* in Table 48 and to other reference numbers throughout the table. Although the guide is conservative, cases may arise where vibration transmission to the building is still excessive. If the problem persists after all short circuits have been eliminated, it can almost always be corrected by increasing isolator deflection, using low-frequency air springs, changing operating speed, improving rotating component balancing, or, as a last resort, changing floor frequency by stiffening or adding more mass. Assistance from a qualified vibration consultant can be very useful in resolving these problems.

Note 1. Isolator deflections shown are based on a reasonably expected floor stiffness according to floor span and class of equipment. Certain spaces may dictate higher levels of isolation. For example, bar joist roofs may require a static deflection of 1.5 in. over factories, but 2.5 in. over commercial office buildings.

Note 2. For large equipment capable of generating substantial vibratory forces and structureborne noise, increase isolator deflection, if necessary, so isolator stiffness is less than one-tenth the stiffness of the supporting structure.

Note 3. For noisy equipment adjoining or near noise-sensitive areas, see the section on Mechanical Equipment Room Sound Isolation.

Note 4. Certain designs cannot be installed directly on individual isolators (type A), and the equipment manufacturer or a vibration specialist should be consulted on the need for supplemental support (base type).

Note 5. Wind load conditions must be considered. Restraint can be achieved with restrained spring isolators (type 4), supplemental bracing, snubbers, or limit stops. Also see Chapter 54.

Note 6. Certain types of equipment require a curb-mounted base (type D). Airborne noise must be considered.

Note 7. See section on Resilient Pipe Hangers and Supports for hanger locations adjoining equipment and in equipment rooms.

Note 8. To avoid isolator resonance problems, select isolator deflection so that resonance frequency is 40% or less of the lowest normal operating speed of equipment (see Chapter 7 in the 2005 *ASHRAE Handbook—Fundamentals*).

Note 9. To limit undesirable movement, thrust restraints (type 5) are required for all ceiling-suspended and floor-mounted units operating at 2 in. of water or more total static pressure.

Note 10. Pumps over 75 hp may need extra mass and restraints.

Note 11. See text for full discussion.

Isolation for Specific Equipment

Note 12. Refrigeration Machines: Large centrifugal, hermetic, and reciprocating refrigeration machines may generate very high noise levels; special attention is required when such equipment is installed in upper-story locations or near noise-sensitive areas. If equipment is located near extremely noise-sensitive areas, follow the recommendations of an acoustical consultant.

Note 13. Compressors: The two basic reciprocating compressors are (1) single- and double-cylinder vertical, horizontal or L-head, which are usually air compressors; and (2) Y, W, and multihead or multicylinder air and refrigeration compressors. Single- and double-cylinder compressors generate high vibratory forces requiring large inertia bases (type C) and are generally not suitable for upper-story locations. If this equipment must be installed in an upper-story location or at-grade location near noise-sensitive areas, the expected maximum unbalanced force data must be obtained from the equipment manufacturer and a vibration specialist consulted for design of the isolation system.

Note 14. Compressors: When using Y, W, and multihead and multicylinder compressors, obtain the magnitude of unbalanced forces from the equipment manufacturer so the need for an inertia base can be evaluated.

Note 15. Compressors: Base-mounted compressors through 5 hp and horizontal tank-type air compressors through 10 hp can be installed directly on spring isolators (type 3) with structural bases (type B) if required, and compressors 15 to 100 hp on spring isolators (type 3) with inertia bases (type C) weighing 1 to 2 times the compressor weight.

Note 16. Pumps: Concrete inertia bases (type C) are preferred for all flexible-coupled pumps and are desirable for most close-coupled pumps, although steel bases (type B) can be used. Close-coupled pumps should not be installed directly on individual isolators (type A) because the impeller usually overhangs the motor support base, causing the rear mounting to be in tension. The primary requirements for type C bases are strength and shape to accommodate base elbow supports. Mass is not usually a factor, except for pumps over 75 hp, where extra mass helps limit excess movement due to starting torque and forces. Concrete bases (type C) should be designed for a thickness of one-tenth the longest dimension with minimum thickness as follows: (1) for up to 30 hp, 6 in.; (2) for 40 to 75 hp, 8 in.; and (3) for 100 hp and up, 12 in.

Pumps over 75 hp and multistage pumps may exhibit excessive motion at start-up ("heaving"); supplemental restraining devices can be installed if necessary. Pumps over 125 hp may generate high starting forces; a vibration specialist should be consulted.

Note 17. Packaged Rooftop Air-Conditioning Equipment: This equipment is usually on lightweight structures that are susceptible to sound and vibration transmission. The noise problem is further compounded by curb-mounted equipment, which requires large roof openings for supply and return air.

The table shows type D vibration isolator selections for all spans up to 20 ft, but extreme care must be taken for equipment located on spans of over 20 ft, especially if construction is open web joists or thin, lightweight slabs. The recommended procedure is to determine the additional deflection caused by equipment in the roof. If additional roof deflection is 0.25 in. or less, the isolator should be selected for 10 times the additional roof deflection. If additional roof deflection is over 0.25 in., supplemental roof stiffening should be installed to bring the roof deflection down below 0.25 in., or the unit should be relocated to a stiffer position.
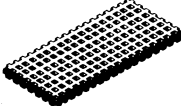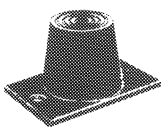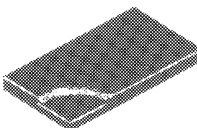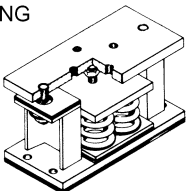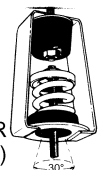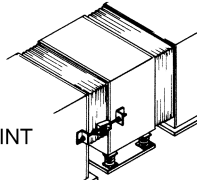
For mechanical units capable of generating high noise levels, mount the unit on a platform above the roof deck to provide an air gap (buffer zone) and locate the unit away from the associated roof penetration to allow acoustical treatment of ducts before they enter the building.
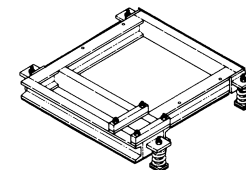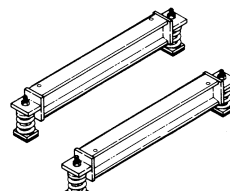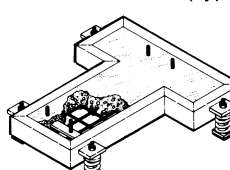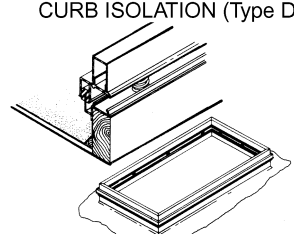
Some rooftop equipment has compressors, fans, and other equipment isolated internally. This isolation is not always reliable because of internal short-circuiting, inadequate static deflection, or panel resonances. It is recommended that rooftop equipment be isolated externally, as if internal isolation was not used.

Note 18. Cooling Towers: These are normally isolated with restrained spring isolators (type 4) directly under the tower or tower dunnage. High-deflection isolators proposed for use directly under the motor-fan assembly must be used with extreme caution to ensure stability and safety under all weather conditions. See Note 5.

Note 19. Fans and Air-Handling Equipment: Consider the following in selecting isolation systems for fans and air-handling equipment:

1. Fans with wheel diameters of 22 in. and less and all fans operating at speeds up to 300 rpm do not generate large vibratory forces. For fans operating under 300 rpm, select isolator deflection so the isolator natural frequency is 40% or less than the fan speed. For example, for a fan operating at 275 rpm, $0.4 \times 275 = 110$ rpm. Therefore, an isolator natural frequency of 110 rpm or lower is required. This can be accomplished with a 3 in. deflection isolator (type 3).

2. Flexible duct connectors should be installed at the intake and discharge of all fans and air-handling equipment to reduce vibration transmission to air duct structures.

3. Inertia bases (type C) are recommended for all class 2 and 3 fans and air-handling equipment because extra mass allows the use of stiffer springs, which limit heaving movements.

4. Thrust restraints (type 5) that incorporate the same deflection as isolators should be used for all fan heads, all suspended fans, and all base-mounted and suspended air-handling equipment operating at 2 in. or more total static pressure. Restraint movement adjustment must be made under normal operational static pressures.

Vibration Isolators: Materials, Types, and Configurations

    Notes 20 through 31 include figures to assist in evaluating commercially available isolators for HVAC equipment. The isolator selected for a particular application depends on the required deflection, life, cost, and compatibility with associated structures.

RUBBER PADS (Type 1)

RUBBER MOUNTS (Type 2)

Note 20. Rubber isolators are available in pad (type 1) and molded (type 2) configurations. Pads are used in single or multiple layers. Molded isolators come in a range of 30 to 70 durometer (a measure of stiffness). Material in excess of 70 durometer is usually ineffective as an isolator. Isolators are designed for up to 0.5 in. deflection, but are used where 0.3 in. or less deflection is required. Solid rubber and composite fabric and rubber pads are also available. They provide high load capacities with small deflection and are used as noise barriers under columns and for pipe supports. These pad types work well only when they are properly loaded and the weight load is evenly distributed over the entire pad surface. Metal loading plates can be used for this purpose.

GLASS FIBER PADS (Type 1)

Note 21. Precompressed glass fiber isolation pads (type 1) constitute inorganic inert material and are available in various sizes, thicknesses of 1 to 4 in., and capacities of up to 500 psi. Their manufacturing process ensures long life and a constant natural frequency of 7 to 15 Hz over the entire recommended load range. Pads are covered with an elastomeric coating to increase damping and to protect the glass fiber. Glass fiber pads are most often used for isolation of concrete foundations and floating floor construction.

SPRING ISOLATOR (Type 3)

RESTRAINED SPRING ISOLATOR (Type 4)

Note 22. Steel springs are the most popular and versatile isolators for HVAC applications because they are available for almost any deflection and have a virtually unlimited life. All spring isolators should have a rubber acoustical barrier to reduce transmission of high-frequency vibration and noise that can migrate down the steel spring coil. They should be corrosion-protected if installed outdoors or in a corrosive environment. The basic types include

    1. **Note 23.** *Open spring isolators* (type 3) consist of a top and bottom load plate with an adjustment bolt for leveling. Springs should be designed with a horizontal stiffness of at least 100% of the vertical stiffness to ensure stability verified by a minimum ratio of 0.8 for the diameter divided by the deflected spring height.

    2. **Note 24.** *Restrained spring isolators* (type 4) have hold-down bolts to limit vertical movement. They are used with (a) equipment with large variations in mass (boilers, refrigeration machines) to restrict movement and prevent strain on piping when water is removed, and (b) outdoor equipment, such as cooling towers, to prevent excessive movement because of wind load. Spring criteria should be the same as open spring isolators, and restraints should have adequate clearance so that they are activated only when a temporary restraint is needed.

    3. *Housed spring isolators* consist of two telescoping housings separated by a resilient material. Although not preferred, if this type is used, care should be taken in design and installation to prevent binding and short-circuiting.

AIR SPRINGS

ROLLING LOBE   BELLOWS

Air springs can be designed for any frequency, but are economical only in applications with natural frequencies of 1.33 Hz or less (6 in. or greater deflection). They do not transmit high-frequency noise and are often used to replace high-deflection springs on problem jobs. A constant air supply (with an air dryer) is required.

RUBBER HANGER (Type 2)

SPRING HANGER (Type 3)

Note 25. Isolation hangers (types 2 and 3) are used for suspended pipe and equipment and have rubber, springs, or a combination of spring and rubber elements. Criteria should be the same as for open spring isolators. To avoid short-circuiting, hangers should be designed for 20 to 35° angular hanger rod misalignment. Swivel or traveler arrangements may be necessary for connections to piping systems subject to large thermal movements.

THRUST RESTRAINT (Type 5)

Note 26. Thrust restraints (type 5) are similar to spring hangers or isolators and are installed in pairs to resist the thrust caused by air pressure.

DIRECT ISOLATION (Type A)

Note 27. Direct isolation (type A) is used when equipment is unitary and rigid and does not require additional support. Direct isolation can be used with large chillers, packaged air-handling units, and air-cooled condensers. If there is any doubt that the equipment can be supported directly on isolators, use structural bases (type B) or inertia bases (type C), or consult the equipment manufacturer.

STRUCTURAL BASES (Type B)	**Note 28.** Structural bases (type B) are used where equipment cannot be supported at individual locations and/or where some means is necessary to maintain alignment of component parts in equipment. These bases can be used with spring or rubber isolators (types 2 and 3) and should have enough rigidity to resist all starting and operating forces without supplemental hold-down devices. Bases are made in rectangular configurations using structural members with a depth equal to one-tenth the longest span between isolators, with a minimum depth of 4 in. Maximum depth is limited to 12 in., except where structural or alignment considerations dictate otherwise.
STRUCTURAL RAILS (Type B)	**Note 29.** Structural rails (type B) are used to support equipment that does not require a unitary base or where the isolators are outside the equipment and the rails act as a cradle. Structural rails can be used with spring or rubber isolators and should be rigid enough to support the equipment without flexing. Usual practice is to use structural members with a depth one-tenth of the longest span between isolators with a minimum depth of 4 in. Maximum depth is limited to 12 in. except where structural considerations dictate otherwise.
CONCRETE BASES (Type C)	**Note 30.** Concrete bases (type C) are used where excess heaving motion may otherwise occur with spring isolators. They consist of a steel pouring form usually with welded-in reinforcing bars, provision for equipment hold-down, and isolator brackets. Like structural bases, concrete bases should be rectangular or T-shaped and, for rigidity, have a depth equal to one-tenth the longest span between isolators with a minimum of 6 in. Base depth need not exceed 12 in. unless specifically required for mass, rigidity, or component alignment.
CURB ISOLATION (Type D)	**Note 31.** Curb isolation systems (type D) are specifically designed for curb-supported rooftop equipment and have spring isolation with a watertight and airtight curb assembly. The roof curbs are narrow to accommodate the small diameter of the springs within the rails, with static deflection in the 1 to 3 in. range to meet the design criteria described in type 3. Flap-type rubber or metal seals are preferable to a continuous sponge at the perimeter to minimize binding and short-circuiting.

In specifying isolator deflection rather than isolation efficiency or transmissibility, a designer can compensate for floor stiffness and building resonances by selecting isolators that have more deflection than the supporting floor. To apply the information from Table 48, base type, isolator type, and minimum deflection columns are added to the equipment schedule. These isolator specifications are then incorporated into mechanical specifications for the project.

Minimum deflections in the table are based on the experience of acoustical and mechanical consultants and vibration control manufacturers. Recommended isolator type, base type, and minimum static deflection are reasonable and safe recommendations for 70 to 80% of HVAC equipment installations. The selections are based on concrete equipment room floors 4 to 12 in. thick with typical floor stiffness. The type of equipment, proximity to noise-sensitive areas, and type of building construction may alter these choices.

The following method develops isolator selection for specific applications:

1. Use Table 48 for floors specifically designed to accommodate mechanical equipment.
2. Use recommendations from the 20 ft span column for equipment on ground-supported slabs adjacent to noise-sensitive areas.
3. For roofs and floors constructed with open web joists; thin, long span slabs; wooden construction; and any unusual light construction, evaluate all equipment weighing more than 300 lb to determine the additional deflection of the structure caused by the equipment. Isolator deflection should be 15 times the additional deflection or the deflection shown in Table 48, whichever is greater. If the required spring isolator deflection exceeds commercially available products, consider air springs, stiffen the supporting structure, or change the equipment location.
4. When mechanical equipment is adjacent to noise-sensitive areas, isolate mechanical equipment room noise.

INTERNAL VERSUS EXTERNAL ISOLATION

Vibration isolators are most effective if the isolator base is attached directly to the building structure at a support point possessing high stiffness compared to the stiffness of the isolator. In many cases, the vibrating equipment (e.g., air-handling units) can be effectively isolated with internal vibration isolators, where only the moving parts (e.g., fan/motor assembly) are supported by the isolators. This approach can reduce the load supported by the isolators and thus can reduce the cost of isolation. The other primary advantage of internal isolation is reduction of vibration and structureborne noise into the air-handling unit housing. Disadvantages of internal isolation can include the following:

- The isolator is often not easily visible in the field to verify that it is functioning properly.
- The isolator support point may be near the middle of a beam, which often provides inadequate stiffness for optimum isolator performance.
- Isolator short-circuiting (caused by horizontal thrust of the fan during normal operation) can significantly degrade internal vibration isolation of internal seismic spring mountings.

It is possible to use both internal and external vibration isolation in the same air-handling unit, but isolator stiffness selection must

avoid resonances at or near normal fan rotational speeds. When both internal and external vibration isolation are used in the same unit, there are multiple resonance frequencies to consider. If the fan operates at or near one of these frequencies, vibration levels could become excessive. The probability of such an interaction increases significantly if the fan is driven by a variable-frequency drive. Implementing both internal and external vibration isolation on the same unit should only be attempted with the guidance of an experienced vibration consultant.

ISOLATION OF VIBRATION AND NOISE IN PIPING SYSTEMS

All piping systems have mechanical vibration generated by the equipment and impeller-generated and flow-induced vibration and noise, which is transmitted by the pipe wall and the water column. In addition, equipment supported by vibration isolators exhibits some motion from pressure thrusts during operation. Vibration isolators have even greater movement during start-up and shutdown as equipment vibration passes through the isolators' resonance frequency. The piping system must be flexible enough to (1) reduce vibration transmission along the connected piping, (2) allow equipment movement without reducing the performance of vibration isolators, and (3) accommodate equipment movement or thermal movement of the piping at connections without imposing undue strain on the connections and equipment.

Flow noise and vibration in piping can be reintroduced by turbulence, sharp pressure drops, and entrained air; however, this can be minimized by sizing pipe so that velocities are 4 fps maximum for pipe 2 in. and smaller and using a pressure drop limitation of 4 ft of water per 100 ft of pipe length with a maximum velocity of 10 fps for larger pipe sizes. Care should be taken not to exceed these limits.

Resilient Pipe Hangers and Supports

Resilient pipe hangers and supports may be used to prevent vibration and noise transmission from the piping system to the building structure and to provide flexibility in the piping.

Suspended Piping. Isolation hangers described in Note 25 of Table 48 should be used for all piping in equipment rooms and up to 50 ft from vibrating equipment. To avoid reducing the effectiveness of equipment isolators, at least the first three hangers from the equipment should provide the same deflection as the equipment isolators, with a maximum limitation of 2 in. deflection; the remaining hangers should be spring or combination spring and rubber with 0.75 in. deflection.

The first two hangers adjacent to the equipment should be the positioning or precompressed type, to prevent load transfer to equipment flanges when the piping system is filled. The positioning hanger aids in installing large pipe, and many engineers specify this type for all isolated pipe hangers for piping 8 in. and larger.

Piping over 2 in. in diameter and piping suspended below or near noise-sensitive areas should be hung with isolation hangers. Hangers adjacent to noise-sensitive areas should be the spring and rubber combination type 3.

Floor-Supported Piping. Floor supports for piping in equipment rooms and adjacent to isolated equipment should use vibration isolators as described in Table 48. They should be selected according to the guidelines for hangers. The first two adjacent floor supports should be the restrained spring type, with a blocking feature that prevents load transfer to equipment flanges as the piping is filled or drained. Where pipe is subjected to large thermal movement, a slide plate (PTFE, graphite, or steel) should be installed on top of the isolator, and a thermal barrier should be used when rubber products are installed directly beneath steam or hot-water lines.

Riser Supports, Anchors, and Guides. Many piping systems have anchors and guides, especially in the risers, to permit expansion joints, bends, or pipe loops to function properly. Anchors and guides are designed to eliminate or limit (guide) pipe movement and must be rigidly attached to the structure; this is inconsistent with the resiliency required for effective isolation. The engineer should try to locate the pipe shafts, anchors, and guides in noncritical areas, such as next to elevator shafts, stairwells, and toilets, rather than adjoining noise-sensitive areas. Where concern about vibration transmission exists, some type of vibration isolation support or acoustical support is required for pipe supports, anchors, and guides.

Because anchors or guides must be rigidly attached to the structure, the isolator cannot deflect in the sense previously discussed, and the primary interest is that of an acoustical barrier. Heavy-duty rubber pads that can accommodate large loads with minimal deflection can provide such an acoustical barrier. Figure 39 shows some arrangements for resilient anchors and guides. Similar resilient supports can be used for the pipe.

Resilient supports for pipe, anchors, and guides can attenuate noise transmission, but they do not provide the resiliency required to isolate vibration. Vibration must be controlled in an anchor guide system by designing flexible pipe connectors and resilient isolation hangers or supports.

Completely spring-isolated riser systems that eliminate the anchors and guides have been used successfully in many instances and

PIPE CLAMP WELDED TO PIPE FOR ANCHOR; OVERSIZED FOR GUIDE

RESILIENTLY ISOLATED PIPE ANCHORS AND GUIDES

PIPE CLAMP WELDED TO PIPE

SPRING-ISOLATED RISER SYSTEM

SPRING MOUNT   PAD MOUNT   RUBBER MOUNT

CONVENTIONAL ISOLATORS AS PIPE SUPPORTS FOR LINES WITH EXPANSION JOINTS
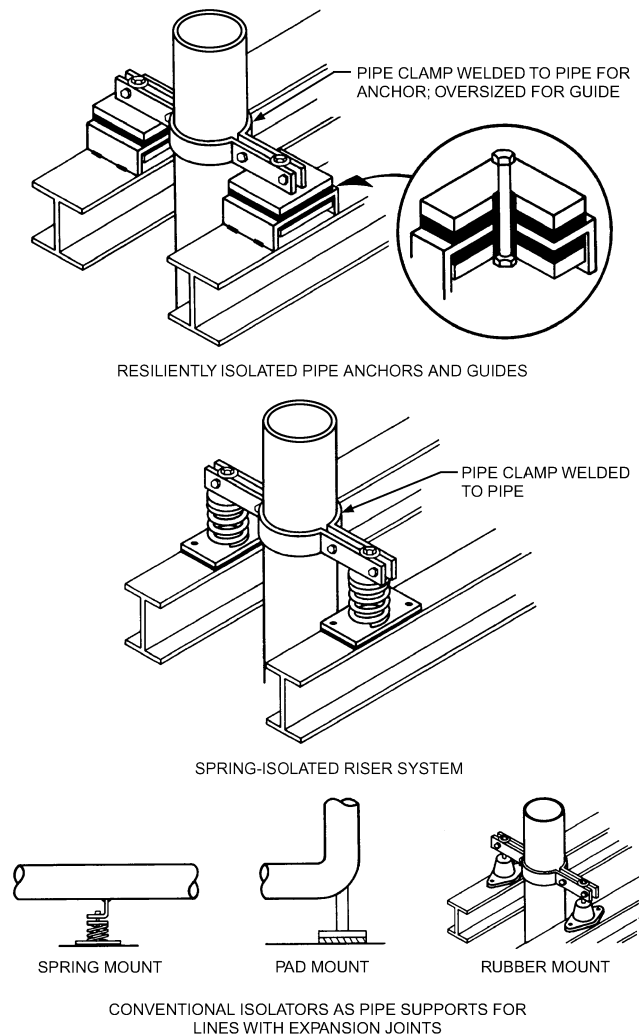
Fig. 39   Resilient Anchors and Guides for Pipes
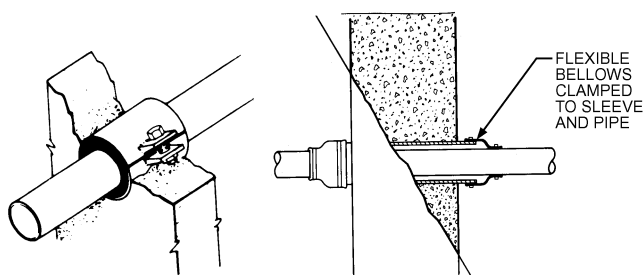
Fig. 40   Acoustical Pipe Penetration Seals

give effective vibration and acoustical isolation. In this type of isolation system, the springs are sized to accommodate thermal growth as well as to guide and support the pipe. These systems provide predictable load transfer because of thermal expansion and contraction, but require careful engineering to accommodate movements encountered not only in the riser but also in the branch takeoff to avoid overstressing the piping.

Piping Penetrations. HVAC systems typically have piping that must penetrate floors, walls, and ceilings. If these penetrations are not properly treated, they provide a path for airborne noise, which can destroy the acoustical integrity of the occupied space. Seal openings in pipe sleeves between noisy areas, such as equipment rooms, and occupied spaces with an acoustical barrier such as fibrous material and resilient acoustical caulking, or with engineered pipe penetration seals as shown in Figure 40.

Flexible Pipe Connectors. Flexible pipe connectors (1) provide piping flexibility to permit isolators to function properly, (2) protect equipment from strain caused by misalignment and expansion or contraction of piping, and (3) attenuate noise and vibration transmission along the piping (Figure 41). Connectors are available in two configurations: (1) hose type, a straight or slightly corrugated wall construction of either rubber or metal; and (2) arched or expansion-joint type, a short-length connector with one or more large-radius arches, of rubber, PTFE, or metal. Metal expansion joints are acoustically ineffective and are seldom successfully used for vibration and sound isolation in HVAC systems; they should not be expected to substitute for conventional pipe vibration isolators.

To accommodate pressure thrust, flexible connectors require an end restraint, which is either (1) added to the connector, (2) incorporated by its design, (3) added to the piping system (anchoring), or (4) built in by the stiffness of the system. Connector extension caused by pressure thrust on isolated equipment should also be considered when flexible connectors are used. Overextension causes failure. Manufacturers' recommendations on restraint, pressure, and temperature limitations must be strictly observed.

Hose Connectors. Hose connectors accommodate lateral movement perpendicular to length and have very limited or no axial movement capability. Rubber hose connectors can have molded or hand-wrapped construction with wire reinforcing, and are available with metal-threaded end fittings or integral rubber flanges. Application of threaded fittings should be limited to 3 in. and smaller pipe diameter. The fittings should be the mechanically expanded type to minimize the possibility of pressure thrust blowout. Flanged types are available in larger pipe sizes. Table 49 lists recommended lengths.

Metal hose is constructed with a corrugated inner core and a braided cover, which helps attain a pressure rating and provides end restraints that eliminate the need for supplemental control assemblies. Short lengths of metal hose or corrugated metal bellows, or pump connectors, are available without braid and have built-in control assemblies. Metal hose is used to control misalignment and vibration rather than noise and is used primarily where temperature or pressure of flow media precludes the use of other material. Table 49 provides recommended lengths.
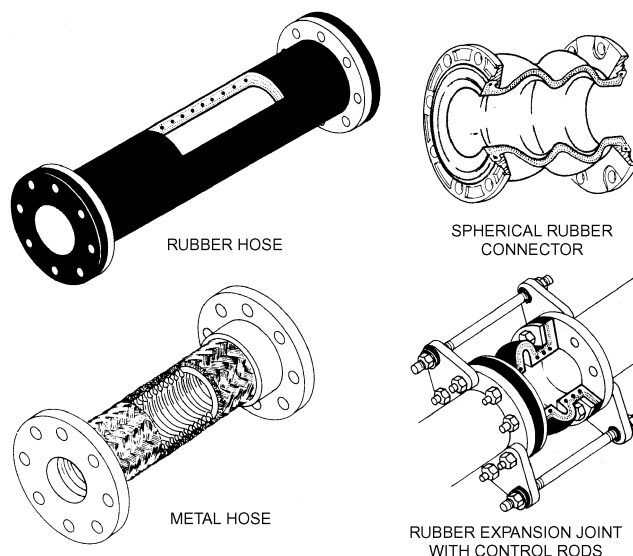
Fig. 41   Flexible Pipe Connectors

Table 49   Recommended Live Lengths[a] of Flexible Rubber and Metal Hose

Nominal Diameter, in.	Length,[b] in.	Nominal Diameter, in.	Length,[b] in.
0.75	12	4	18
1	12	5	24
1.5	12	6	24
2	12	8	24
2.5	12	10	24
3	18	12	36

[a]Live length is end-to-end length for integral flanged rubber hose and is end-to-end less total fitting length for all other types.
[b]Per recommendations of Rubber Expansion Division, Fluid Sealing Association.

Expansion Joint or Arched Connectors. Expansion joint or arched connectors have one or more convolutions or arches and can accommodate all modes of axial, lateral, and angular movement and misalignment. When made of rubber, they are commonly called expansion joints, spool joints, or spherical connectors; in PTFE, they are known as couplings or expansion joints.

Rubber expansion or spool joints are available in two basic types: (1) hand-wrapped with wire and fabric reinforcing, and (2) molded with fabric and wire or with high-strength fabric only (instead of metal) for reinforcing. The handmade type is available in a variety of materials and lengths for special applications. Rubber spherical connectors are molded with high-strength fabric or tire cord reinforcing instead of metal. Their distinguishing characteristic is a large-radius arch. The shape and construction of some designs allow use without control assemblies in systems operating to 150 psi, and are the most effective for minimizing transmission of vibration. Where thrust restraints are not built in, they must be used as described for rubber hose joints.

PTFE expansion joints and couplings are similar in construction to rubber expansion joints with reinforcing metal rings.

In evaluating these devices, consider temperature, pressure, and service conditions as well as each device's ability to attenuate vibration and noise. Metal hose connections can accommodate misalignment and attenuate mechanical vibration transmitted through the pipe wall, but do little to attenuate noise. This type of connector has superior resistance to long-term temperature effects. Rubber hose, expansion joints, and spherical connectors attenuate vibration and impeller-generated noise transmitted through the pipe wall. Because rubber expansion joint and spherical connector

walls are flexible, they have the ability to grow volumetrically and attenuate noise and vibration at blade-pass frequencies. This is a particularly desirable feature in uninsulated piping systems, such as for condenser or domestic water, which may run adjacent to noise-sensitive areas. However, high pressure has a detrimental effect on the ability of the connector to attenuate vibration and noise.

Because none of the flexible pipe connectors control flow or velocity noise or completely isolate vibration and noise transmission to the piping system, resilient pipe hangers and supports should be used; these are shown in Note 25 for Table 48 and are described in the Resilient Pipe Hangers and Supports section.

Isolating Duct Vibration

Flexible canvas and rubber duct connections should be used at fan intake and discharge. However, they are not completely effective because they become rigid under pressure, allowing the vibrating fan to pull on the duct wall. To maintain a slack position of the flexible duct connections, thrust restraints (see Note 26, Table 48) should be used on all equipment as indicated in Table 48.

Although vibration transmission from ducts isolated by flexible connectors is not common, flow pulsations within the duct can cause mechanical vibration in the duct walls, which can be transmitted through rigid hangers. Spring or combination spring and rubber hangers are recommended wherever ducts are suspended below or near a noise-sensitive area.

SEISMIC PROTECTION

Seismic restraint requirements are specified by applicable building codes that define design forces to be resisted by the mechanical system, depending on building location and occupancy, location of the system in the building, and whether it is used for life safety. Where required, seismic protection of resiliently mounted equipment poses a unique problem, because resiliently mounted systems are much more susceptible to earthquake damage from overturning forces, the impact limits of bare restraints, and resonances inherent in vibration isolators.

A deficiency in seismic restraint design or anchorage may not become apparent until an earthquake occurs, with possible catastrophic consequences. Adequacy of the restraint system and anchorage to resist code design forces must be verified before the event, by either equipment tests, calculations, or dynamic analysis, depending on the item, with calculations or dynamic analysis performed under the direction of a professional engineer. These analysis items may be supplied as a package by the vibration isolation vendor.

Restraints for floor-mounted equipment should be designed with adequate clearances so that they are not engaged during normal operation of the equipment. Contact surfaces (snubbers) should be protected with resilient pad material to limit shock during an earthquake, and restraints should be strong enough to resist the forces in any direction. The integrity of these devices can be verified by a comprehensive analysis, but is more frequently verified by laboratory tests.

Calculations or dynamic analyses should have an engineer's seal to verify that input forces are obtained in accordance with code or specification requirements. Additionally, a professional engineer should make the anchorage calculations in accordance with accepted standards. For more information, see Chapter 54.

VIBRATION INVESTIGATIONS

Theoretically, a vibration isolation system can be designed to mitigate even the most extreme sources of mechanical vibration. However, isolators should not be used to mask a condition that should be corrected before it damages the equipment and its operation. High vibration levels can indicate a faulty equipment operating

condition in need of correction, or they can be a symptom of a resonance interaction between a vibrating piece of equipment and the structure(s) on which it is supported or to which it is attached.

Vibration investigations can include

- Measurement of vibration levels on vibrating equipment (see Figure 38 for recommended vibration criteria)
- Measurement of vibration levels in building structures to which vibrating equipment is connected, such as a building floor, piping systems, etc. (see Figure 37 and Table 46 for recommended building vibration criteria)
- Examination of equipment vibration generated by system components, such as bearings, drives, pumps, etc.
- Measurement of the natural frequencies (resonances) of vibrating equipment or connected structure(s)
- Examination of equipment installation factors, such as equipment alignment, vibration isolator placement, etc. (see Table 48)
- Measurement of the unbalance of reciprocating or rotating equipment components

TROUBLESHOOTING

Despite all precautions, situations may arise where there is disturbing noise and vibration. Problems can be identified and corrected by

- Determining which equipment or system is the source of the problem
- Determining whether the problem is one of airborne sound, vibration (structure-borne noise), or a combination of both
- Applying appropriate solutions

Troubleshooting can be time-consuming, expensive, and difficult. Once a noise or vibration transmission problem exists, occupants become more sensitive and require greater reduction of the sound and vibration levels than would initially have been satisfactory. The need for troubleshooting should be minimized by carefully designing, installing, and testing the system as soon as it is operational and before the building is occupied.

DETERMINING PROBLEM SOURCE

The system or equipment that is the source of the problem can often be determined without instrumentation. Vibration and noise levels are usually well above the sensory level of perception and are readily felt or heard. A simple, accurate method of determining the problem source is to turn individual pieces of equipment on and off until the vibration or noise is eliminated. Because the source of the problem is often more than one piece of equipment or the interaction of two or more systems, it is always good practice to double check by shutting off the system and operating the equipment individually. Reynolds and Bevirt (1994) and Schaffer (2005) provide practical information on the measurement and assessment of sound and vibration in buildings.

DETERMINING PROBLEM TYPE

Once the source is identified, the next step is to determine whether the problem is one of noise or vibration. Clearly perceptible vibration is often a clue that vibration transmission is the major cause of the problem. The possibility that lightweight wall or ceiling panels are excited by airborne noise should be considered. Even if the vibration is not readily perceptible, however, the problem may still be one of vibration transmission causing structureborne noise. This can be checked using the following procedure:

1. If a sound level meter is available, check C-weighted and overall (unweighted or linear) readings. If the difference between them is greater than 6 dB, or if the slope of the acoustic spectrum is

steeper than 6 dB per octave at low frequencies, vibration is likely a contributing factor.

2. If excessive noise is found close to the equipment and/or main ductwork, airborne noise is probably the main contributor.

3. If the affected area is remote from source equipment, there is no problem in intermediary spaces, and noise does not appear to be coming from the duct system or diffusers, structureborne noise is probably the cause.

One important step in diagnosing many noise or vibration problems, particularly if the affected area is close to the mechanical equipment room, is to check the equipment's vibration isolation system. A simple test is to have one person listen in the affected area while another shouts loudly in the equipment room. If the voice cannot be heard, the problem is likely one of structure-borne noise. If the voice can be heard, check for openings in the wall or floor separating the areas. If no such openings exist, the structure separating the areas does not provide adequate transmission loss. In these situations, see the section on Mechanical Equipment Room Sound Isolation for possible solutions.

Noise Problems

If ductborne sound (i.e., noise from grilles or diffusers or duct breakout noise) appears to be the problem, measure the sound-pressure levels and compare them with the design criteria (NC, RC, etc.). It is often helpful to obtain sound data with and without terminal devices installed. Comparison of the two results shows how much noise a given terminal device contributes. If this reveals the responsible components, the engineer can analyze each sound source using the procedures presented in this chapter to determine whether sufficient attenuation has been provided.

If the sound source is a fan, pump, or similar rotating equipment, an important question is whether it is operating near the most efficient part of its operating curve, where most equipment operates best. Excessive vibration and noise can occur if a fan or pump is trying to move too little or too much air or water. Check that vanes, dampers, and valves are in the correct operating position and that the system has been properly balanced.

Vibration Problems

Vibration and structureborne noise problems can occur from

- Equipment operating with excessive levels of vibration, caused by poor balance, misalignment, or other improper condition internal to equipment
- Inadequate vibration isolators
- Improperly selected or installed vibration isolators that do not provide the required isolator static deflection
- Flanking transmission paths such as rigid pipe connections, obstructions under the base of vibration-isolated equipment, or isolator deflection limiters (for earthquake or shipping protection) being improperly engaged
- Excessive floor flexibility
- Resonances in equipment, vibration isolation system, building structure, or connected structures (e.g., piping)

Most field-encountered problems result from improperly selected or installed isolators and flanking paths of transmission, which can be simply evaluated and corrected. If the equipment lacks vibration isolators, in many cases it is possible to add isolators (see Table 48) without altering connected ducts or piping by using structural brackets. Floor flexibility and resonance problems are sometimes encountered and usually require analysis by experts. However, the procedures in the following sections can help identify such problems.

Testing Vibration Isolation Systems. Improperly functioning vibration isolation systems are the cause of most field-encountered problems and can be evaluated and corrected by the following procedures:

1. Ensure that the system is free-floating by bouncing the base, which should cause the equipment to move up and down freely and easily. On floor-mounted equipment, check that there are no obstructions between the base and the floor that would short-circuit the isolation system. This is best accomplished by passing a rod under the equipment. A small obstruction might allow the base to rock, giving the impression that it is free-floating when it is not. On suspended equipment, make sure that rods are not touching the hanger box. Rigid connections such as pipes and ducts can prevent equipment from floating freely, prohibit isolators from functioning properly, and provide flanking paths for vibration transmission.

2. Determine whether isolator static deflection is as specified or required, changing it if necessary, as recommended in Table 48. A common problem is inadequate deflection caused by underloaded isolators. Overloaded isolators are not generally a problem as long as the system is free-floating and there is space between the spring coils.

With most commonly used spring isolators, static deflection can be determined by measuring the operating height and comparing it to free-height information available from the manufacturer. Once the actual isolator deflection is known, determine its adequacy by comparing it with the recommended deflection in Table 48.

The efficiency of a vibration isolator depends on the ratio of the forcing frequency to the natural frequency of the isolator. If the natural frequency of the isolator is less than 25% of the forcing frequency (usually considered the operating speed of the equipment), the isolator will operate at an efficiency of 95% or greater, and generally provides sufficient vibration isolation except in solutions where heavy equipment is installed on extremely long-span floors or very flexible floors or roofs. If a transmission problem exists, it may be caused by (1) excessively rough equipment operation, (2) the system not being free-floating or flanking path transmission, or (3) a resonance or floor stiffness problem.

It is easy to determine the natural frequency of spring isolators from the static deflection determined by spring height measurements, but these measurements are difficult with pad and elastomeric isolators and are often not accurate in determining their natural frequencies. Although such isolators can theoretically provide natural frequencies as low as 4 Hz, they typically provide higher natural frequencies and generally do not provide the desired isolation efficiencies for upper floor equipment locations.

In general, it is very difficult to determine whether vibration isolation efficiencies intended in design have been achieved in field installations using field vibration measurements. However, vibration measurements can readily be made on vibrating equipment, equipment supports, floors supporting vibration-isolated equipment, and floors in adjacent areas to determine whether vibration criteria specified in Table 46 or in Figures 37 and 38 have been achieved.

Floor Flexibility Problems. Floor flexibility problems can occur with heavy equipment installed on long-span floors or thin slabs and with rooftop equipment installed on light structures of open web joist construction. If floor flexibility is suspected, the isolators should be one-tenth or less as stiff as the floor to eliminate the problem. Floor stiffness can be determined by calculating the additional floor deflection caused by a specific piece of equipment.

For example, if a 10,000 lb piece of equipment causes floor deflection of an additional 0.1 in., floor stiffness is 100,000 lb/in., and an isolator combined stiffness of 10,000 lb/in. or less must be used. Note that floor stiffness or spring rate, not total floor deflection, is determined. In this example, the total floor deflection might be 1 in., but if the problem equipment causes 0.1 in. of that deflection, 0.1 in. is the factor that identifies floor stiffness of 100,000 lb/in.

Resonance Problems. These problems occur when the equipment's operating speed is the same as or close to the resonance

frequency of (1) an equipment component such as a fan shaft or bearing support pedestal, (2) the vibration isolation system, or (3) the resonance frequency of the floor or other building component, such as a wall. Vibration resonances can cause excessive equipment vibration levels, as well as objectionable and possibly destructive vibration transmission in a building. These conditions must always be identified and corrected.

When vibrating mechanical equipment is mounted on vibration isolators on a flexible floor, there are two resonance frequencies that must be considered: that of the floor and that of the isolated equipment. The lower frequency should be controlled by the stiffness (and consequently the static deflection) of the vibration isolators. This frequency should be significantly less than the normal operating speed (or frequency) of the mechanical equipment and is generally not a problem. The higher resonance frequency is associated with and primarily controlled by the stiffness of the supporting structure. This resonance frequency is usually not affected by increasing or decreasing the static deflection of the mechanical equipment vibration isolators.

Sometimes, when the floor under mechanical equipment is flexible (as occurs with some long-span floor systems and with roof systems supporting rooftop packaged units), the operating speed of the mechanical equipment can coincide with the floor resonance frequency. When this occurs, changing the static deflection of the vibration isolators may not solve the problem. Alternatives include changing the rotating speed of the equipment, stiffening the structure, or adjusting a variable-frequency drive to avoid the resonant frequency.

Vibration Isolation System Resonance. Always characterized by excessive equipment vibration, vibration isolation system rigid-body resonance (characterized by the mass of the equipment vibrating on the stiffness of the isolators) usually results in objectionable transmission to the building structure. However, transmission might not occur if the equipment is on grade or on a stiff floor. Vibration isolation system rigid-body resonances can be measured with instrumentation or, more simply, by determining the isolator natural frequency as described in the section on Testing Vibration Isolation Systems and comparing this figure to the operating speed of the equipment.

When a vibration isolation system resonance problem exists, the system natural frequency must be changed using the following guidelines:

- If equipment is installed on excessively stiff pad or rubber elastomeric mounts, isolators with the deflection recommended in Table 48 should be installed.
- If equipment is installed on spring isolators and there is objectionable vibration or noise transmission to the structure, determine whether the isolator is providing the designed static deflection. For example, an improperly selected or installed nominal 2 in. deflection isolator could be experiencing only 1/8 in. deflection under its static load, which would be in resonance with equipment operating at 500 rpm. If this is the case, the isolators should be replaced with ones having enough capacity to provide the requisite 2 in. deflection. However, if there is no transmission problem with the isolators, it is not necessary to use greater-deflection isolators than can be conveniently installed.
- If equipment is installed on spring isolators and there is objectionable noise or vibration transmission, replace the isolators with springs of the deflection recommended in Table 48.
- If equipment is installed on spring isolators of the recommended stiffness and there is objectionable high-frequency (200 Hz or greater) noise or vibration, it is possible that resonances internal to the spring are the culprit. These resonances, sometimes called surge frequencies, can be important in applications where equipment (e.g., screw compressors, inverters) generates high-frequency noise. To control their adverse effects, many isolator designs

incorporate an elastomeric pad under the spring. It may also be possible to identify an elastomeric mount that can provide the desired static deflection; these typically have better high-frequency characteristics than springs.

Building Resonances. These problems occur when some part of the structure has a resonance frequency coincident with the disturbing frequency (often the operating speed) of some of the equipment. These problems can exist even if the isolator deflections recommended in Table 48 are used. The resulting objectionable noise or vibration should be evaluated and corrected. Often, the resonance problem is associated with the floor on which the equipment is installed, but it can also occur in a remotely located floor, wall, or other building component. If a noise or vibration problem has a remote source that cannot be associated with piping or ducts, building resonance must be suspected.

Building resonance problems can be resolved by the following:

- Reduce the vibration force by balancing the equipment. This is not a practical solution for a true resonance problem. However, it is effective when the disturbing frequency is close to the floor's natural frequency, as evidenced by the equal displacement of the floor and the equipment, especially when the equipment is operating with excessive vibration.
- Change the disturbing frequency by changing the equipment operating speed. This is practical only for belt-driven equipment, or equipment driven by variable-frequency drives.

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Acoustical Society of America (ASA). . . . . asa.aip.org
Vibration Institute . . . . www.vibinst.org
North American Insulation Manufacturers
    Association (NAIMA) . . . . www.naima.org
International Agency for Research on Cancer
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CHAPTER 48

WATER TREATMENT

THIS chapter covers the fundamentals of water treatment and some of the common problems associated with water in heating and air-conditioning equipment.

WATER CHARACTERISTICS

Chemical Characteristics

When rain falls, it dissolves carbon dioxide and oxygen in the atmosphere. The carbon dioxide mixes with the water to form carbonic acid (H_2CO_3). When carbonic acid contacts soil that contains limestone ($CaCO_3$), it dissolves the calcium to form calcium carbonate. Calcium carbonate in water used in heating or air-conditioning applications can eventually become scale, which can increase energy costs, maintenance time, equipment shutdowns, and could eventually lead to equipment replacement.

The following paragraphs discuss typical chemical and physical properties of water used for HVAC applications.

Alkalinity is a measure of the capacity to neutralize strong acids. In natural waters, the alkalinity almost always consists of bicarbonate, although some carbonate may also be present. Borate, hydroxide, phosphate, and other constituents, if present, are included in the alkalinity measurement in treated waters. Alkalinity also contributes to scale formation.

Alkalinity is measured using two different end-point indicators. The **phenolphthalein alkalinity** (P alkalinity) measures the strong alkali present; the **methyl orange alkalinity** (M alkalinity), or **total alkalinity**, measures the total alkalinity in the water. Note that the total alkalinity includes the phenolphthalein alkalinity. For most natural waters, in which the concentration of phosphates, borates, and other noncarbonated alkaline materials is small, the actual chemical species present can be estimated from the two alkalinity measurements (Table 1).

Alkalinity or acidity is often confused with pH. Such confusion may be avoided by keeping in mind that the pH is a measure of hydrogen ion concentration expressed as the logarithm of its reciprocal.

Chlorides have no effect on scale formation but do contribute to corrosion because of their conductivity and because the small size of the chloride ion permits the continuous flow of corrosion current when surface films are porous. The amount of chlorides in the water is a useful measuring tool in evaporative systems. Virtually all other constituents in the water increase or decrease when common treatment chemicals are added or because of chemical changes that take place in normal operation. With few exceptions, only evaporation affects chloride concentration, so the ratio of chlorides in a water sample from an operating system to those of the makeup water provides a measure of how much the water has been concentrated. (*Note*: Chloride levels will change if the system is continuously chlorinated.)

Dissolved solids consist of salts and other materials that combine with water as a solution. They can affect the formation of corrosion and scale. Low-solids waters are generally corrosive because they have less tendency to deposit protective scale. If a high-solids

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Table 1 Alkalinity Interpretation for Waters[a]

If	Then, Carbonate	Bicarbonate	Free CO$_2$
P Alk = 0	0	M Alk	Present
P Alk < 0.5M Alk	2P Alk	M Alk − 2P Alk	0
P Alk = 0.5M Alk	2P Alk = M Alk	0	0
P Alk > 0.5M Alk [b]	2(M Alk − P Alk)	0	0

[a] P Alk = Phenolphthalein alkalinity. M Alk = Methyl orange (total) alkalinity.
[b] Treated waters only. Hydroxide also present.

water is nonscaling, it tends to produce more intensive corrosion because of its high conductivity. Dissolved solids are often referred to as total dissolved solids (TDS).

Conductivity or **specific conductance** measures the ability of a water to conduct electricity. Conductivity increases with the total dissolved solids. Specific conductance can be used to estimate total dissolved solids.

Silica can form particularly hard-to-remove deposits if allowed to concentrate. Fortunately, silicate deposition is less likely than other deposits.

Soluble iron in water can originate from metal corrosion in water systems or as a contaminant in the makeup water supply. The iron can form heat-insulating deposits by precipitation as iron hydroxide or iron phosphate (if a phosphate-based water treatment product is used or if phosphate is present in the makeup water).

Sulfates also contribute to scale formation in high-calcium waters. Calcium sulfate scale, however, forms only at much higher concentrations than the more common calcium carbonate scale. High sulfates also contribute to increased corrosion because of their high conductivity.

Suspended solids include both organic and inorganic solids suspended in water (particularly unpurified water from surface sources or those that have been circulating in open equipment). Organic matter in surface supplies may be colloidal. Naturally occurring compounds such as lignins and tannins are often colloidal. At high velocities, hard suspended particles can abrade equipment. Settled suspended matter of all types can contribute to concentration cell corrosion.

Turbidity can be interpreted as a lack of clearness or brilliance in a water. It should not be confused with color. A water may be dark in color but still clear and not turbid. Turbidity is due to suspended matter in a finely divided state. Clay, silt, organic matter, microscopic organisms, and similar materials are contributing causes of turbidity. Although suspended matter and turbidity are closely related they are not synonymous. Suspended matter is the quantity of material in a water that can be removed by filtration. The turbidity of water used in HVAC systems should be as low as possible. This is particularly true of boiler feedwater. The turbidity can concentrate in the boiler and may settle out as sludge or mud and lead to deposition. It can also cause increased boiler blowdown, plugging, overheating, priming, and foaming.

Biological Characteristics

Bacteria, algae, and fungi can be present in water systems, and their growth can cause operating, maintenance, and health problems.

Microorganism growth is affected by temperature, food sources, and water availability. Biological growth can occur in most water systems below 150°F. Problems caused by biological materials range from green algae growth in cooling towers to slime formation from bacteria in secluded and dark areas. The result can be plugging of equipment where flow is essential. Dead algae are often characterized by foul odors and mud-like deposits, which are often high in silica from the cell walls of the diatoms. These problems can be eliminated, or at least reduced to reasonable levels, by mechanical or chemical treatment.

CORROSION CONTROL

Corrosion is the destruction of a metal or alloy by chemical or electrochemical reaction with its environment. In most instances, this reaction is electrochemical in nature, much like that in an electric battery. For corrosion to occur, a corrosion cell consisting of an anode, a cathode, an electrolyte, and an electrical connection must exist. Metal ions dissolve into the electrolyte (water) at the anode. Electrically charged particles (electrons) are left behind. These electrons flow through the metal to other points (cathodes) where electron-consuming reactions occur. The result of this activity is the loss of metal and often the formation of a deposit.

Types of Corrosion

Corrosion can often be characterized as general, localized or pitting, galvanic, caustic cracking, corrosion fatigue, erosion corrosion, and microbiological corrosion.

General corrosion is uniformly distributed over the metal surface. The considerable amount of iron oxide produced by generalized corrosion contributes to fouling.

Localized or pitting corrosion exists when only small areas of the metal corrode. Pitting is the most serious form of corrosion because the action is concentrated in a small area. Pitting may perforate the metal in a short time.

Galvanic corrosion can occur when two different metals are in contact. The more active (less noble) metal corrodes rapidly. Common examples of galvanic corrosion in water systems are steel and brass, aluminum and steel, zinc and steel, and zinc and brass. If galvanic corrosion occurs, the metal named first corrodes.

Corrosion fatigue may occur by one of two mechanisms. In the first mechanism, cyclic stresses (for example, those created by rapid heating and cooling) are concentrated at points where corrosion has roughened or pitted the metal surface. In the second type, cracks often originate where metal surfaces are covered by a dense protective oxide film, and cracking occurs from the action of applied cyclic stresses.

Caustic cracking occurs when metal is stressed, water has a high caustic content, a trace of silica is present, and a mechanism of concentration occurs.

Stress corrosion cracking can occur in alloys exposed to a characteristic corrosive environment and subject to tensile stress. The stress may be either applied, residual (from processing), or a combination. The resulting crack formation is generally intergranular.

Erosion corrosion occurs as a result of flow or impact that physically removes the protective metal oxide surface. This type of corrosion usually takes place due to altered flow patterns or a flow rate that is above design.

Microbiologically influenced corrosion occurs when bacteria secrete corrosive acids on the metal surface. Often bacteria commingle with dirt and silt that protect the bacteria from biocides.

Factors That Contribute to Corrosion

Moisture. Corrosion does not occur in dry environments. However, some moisture is present as water vapor in most environments. In pure oxygen, almost no iron corrosion occurs at relative humidities up to 99%. However, when contaminants such as sulfur dioxide or solid particles of charcoal are present, corrosion can proceed at relative humidities of 50% or more. The corrosion reaction proceeds on surfaces of exposed metals such as iron and unalloyed steel as long as the metal remains wet. Many alloys develop protective corrosion-product films or oxide coatings and are thus unaffected by moisture.

Oxygen. In electrolytes consisting of water solutions of salts or acids, the presence of dissolved oxygen accelerates the corrosion rate of ferrous metals by depolarizing the cathodic areas through reaction with hydrogen generated at the cathode. In many systems, such as boilers or water heaters, most of the dissolved oxygen and other dissolved gases are removed from the water by deaeration to reduce the potential for corrosion.

Solutes. In ferrous materials such as iron and steel, mineral acids accelerate the corrosion rate, whereas alkalies decrease it. The likelihood of cathodic polarization, which slows down corrosion, decreases as the concentration of hydrogen ions (i.e., the acidity of the environment) increases. Relative acidity or alkalinity of a solution is defined as pH; a neutral solution has a pH of 7. The corrosivity of most salt solutions depend on their pH. Because alkaline solutions are generally less corrosive to ferrous systems, it is practical in many closed water systems to minimize corrosion by adding alkali or alkaline salt to raise the pH to 9 or higher.

Differential Solute Concentration. For the corrosion reaction to proceed, a potential difference between anode and cathode areas is required. This potential difference can be established between different locations on a metal surface because of differences in solute concentration in the environment at these locations. Corrosion caused by such conditions is called **concentration cell corrosion**. These cells can be metal ions or oxygen concentration cells.

In the metal ion cell, the metal surface in contact with the higher concentration of dissolved metal ion becomes the cathodic area, and the surface in contact with the lower concentration becomes the anode. The metal ions involved may be a constituent of the environment or may come from the corroding surface itself. The concentration differences may be caused by the sweeping away of the dissolved metal ions at one location and not at another.

In an oxygen concentration cell, the surface area in contact with the surface environment of higher oxygen concentration becomes the cathodic area, and the surface in contact with the surface environment of lower oxygen concentration becomes the anode. Crevices or foreign deposits on the metal surface can create conditions that contribute to corrosion. The anodic area, where corrosion proceeds, is in the crevice or under the deposit. Although they are manifestations of concentration cell corrosion, **crevice corrosion** and **deposit attack** are sometimes referred to as separate forms of corrosion.

Galvanic or Dissimilar Metal Corrosion. Another factor that can accelerate the corrosion process is the difference in potential of dissimilar metals coupled together and immersed in an electrolyte. The following factors control the severity of corrosion resulting from such dissimilar metal coupling:

- Relative differences in position (potential) in the galvanic series, with reference to a standard electrode. The greater the difference, the greater the force of the reaction. The galvanic series for metals in flowing aerated seawater is shown in Table 2.

- Relative area relationship between anode and cathode areas. Because the amount of current flow and, therefore, total metal loss is determined by the potential difference and resistance of the circuits, a small anodic area corrodes more rapidly; it is penetrated at a greater rate than a large anodic area.

- Polarization of either the cathodic or anodic area. Polarization can reduce the potential difference and thus reduce the rate of attack of the anode.

- The mineral content of water. As mineral content increases, the resulting higher electrical conductivity increases the rate of galvanic corrosion.

Table 2　Galvanic Series of Metals and Alloys in Flowing Aerated Seawater at 40 to 80°F

Corroded End (Anodic or Least Noble)
Magnesium alloys
Zinc
Beryllium
Aluminum alloys
Cadmium
Mild steel, wrought iron
Cast iron, flake or ductile
Low-alloy high-strength steel
Ni-Resist, Types 1 & 2
Naval Brass (CA464), yellow brass (CA268), Al brass (CA687), red brass (CA230), admiralty brass (CA443), Mn Bronze
Tin
Copper (CA102, 110), Si Bronze (CA655)
Lead-tin solder
Tin bronze (G & M)
Stainless steel, 12 to 14% Cr (AISI types 410,416)
Nickel silver (CA 732, 735, 745, 752, 764, 770, 794)
90/10 Copper-nickel (CA 706)
80/20 Copper-nickel (CA 710)
Stainless steel, 16 to 18% Cr (AISI Types 430)
Lead
70/30 Copper-nickel (CA 715)
Nickel-aluminum bronze
Silver braze alloys
Nickel 200
Silver
Stainless steel, 18% Cr, 8% Ni (AISI Types 302, 304, 321, 347)
Stainless steel, 18% Cr, 12% Ni-Mo (AISI Types 316, 317)
Titanium
Graphite, graphitized cast iron
Protected End (Cathodic or Most Noble)

Stress. Stresses in metallic structures rarely have significant effects on the uniform corrosion resistance of metals and alloys. Stresses in specific metals and alloys can cause corrosion cracking when the metals are exposed to specific corrosive environments. The cracking can have catastrophic effects on the usefulness of the metal.

Almost all metals and alloys exhibit susceptibility to stress corrosion cracking in at least one environment. Common examples are steels in hot caustic solutions, high zinc content brasses in ammonia, and stainless steels in hot chlorides. Metal manufacturers have technical details on specific materials and their resistance to stress corrosion.

Temperature. According to studies of chemical reaction rates, corrosion rates double for every 18°F rise in temperature. However, such a ratio is not necessarily valid for nonlaboratory corrosion reactions. The effect of temperature on a particular system is difficult to predict without specific knowledge of the characteristics of the metals involved and the environmental conditions.

An increase in temperature may increase the corrosion rate, but only to a point. Oxygen solubility decreases as temperature increases and, in an open system, may approach zero as water boils. Beyond a critical temperature level, the corrosion rate may decrease due to a decrease in oxygen solubility. However, in a closed system, where oxygen cannot escape, the corrosion rate may continue to increase with an increase in temperature.

For those alloys, such as stainless steel, that depend on oxygen in the environment for maintaining a protective oxide film, the reduction in oxygen content due to an increase in temperature can accelerate the corrosion rate by preventing oxide film formation.

Temperature can affect corrosion potential by causing a salt dissolved in the environment to precipitate on the metal surface as a protective layer of scale. One example is calcium carbonate scale in hard waters. Temperature can also affect the nature of the corrosion product, which may be relatively stable and protective in certain temperature ranges and unstable and non protective in others. An example of this is zinc in distilled water; the corrosion product is non protective from 140 to 190°F but reasonably protective at other temperatures.

Pressure. Where dissolved gases such as oxygen and carbon dioxide affect the corrosion rate, pressure on the system may increase their solubility and thus increase corrosion. Similarly, a vacuum on the system reduces the solubility of the dissolved gas, thus reducing corrosion. In a heated system, pressure may rise with temperature. It is difficult and impractical to control system corrosion by pressure control alone.

Flow Velocity. The effect of flow velocity on the corrosion rate of systems depends on several factors, including

- Amount of oxygen in the water
- Type of metal (iron and steel are most susceptible)
- Flow rate

In metal systems where corrosion products retard corrosion by acting as a physical barrier, high flow velocities may cause the removal of those protective barriers and increase the potential for corrosion. A turbulent environment may cause uneven attack, from both erosion and corrosion. This corrosion is called **erosion corrosion**. It is commonly found in piping with sharp bends where the flow velocity is high. Copper and softer metals are more susceptible to this type of attack.

Preventive and Protective Measures

Materials Selection. Any piece of heating or air-conditioning equipment can be made of metals that are virtually corrosion-proof under normal and typical operating conditions. However, economics usually dictate material choices. When selecting construction materials the following factors should be considered:

- Corrosion resistance of the metal in the operating environment
- Corrosion products that may be formed and their effects on equipment operation
- Ease of construction using a particular material
- Design and fabrication limitations on corrosion potential
- Economics of construction, operation, and maintenance during the projected life of the equipment, (i.e., expenses may be minimized in the long run by paying more for a corrosion-resistant material and avoiding regular maintenance).
- Use of dissimilar metals should be avoided. Where dissimilar materials are used, insulating gaskets and/or organic coatings must be used to prevent galvanic corrosion.
- Compatibility of chemical additives with materials in the system

Protective Coatings. The operating environment has a significant role in the selection of protective coatings. Even with a coating suited for that environment, the protective material depends on the adhesion of the coating to the base material, which itself depends on the surface preparation and application technique.

Maintenance. Defects in a coating are difficult to prevent. These defects can be either flaws introduced into the coating during application or mechanical damage sustained after application. In order to maintain corrosion protection, defects must be repaired.

Cycles of Concentration. Some corrosion control may be achieved by optimizing the cycles of concentration (the degree to which soluble mineral solids in the makeup water have increased in the circulating water due to evaporation). Generally, adjustment of the blowdown rate and pH to produce a slightly scale-forming condition (see section on Scale Control) will result in an optimum condition between excess corrosion and excess scale.

Chemical Methods. Chemical protective film-forming chemical inhibitors reduce or stop corrosion by interfering with the corrosion mechanism. Inhibitors usually affect either the anode or the cathode.

Anodic corrosion inhibitors establish a protective film on the anode. Though these inhibitors can be effective, they can be dangerous—if insufficient anodic inhibitor is present, the entire corrosion

Table 3   Typical Corrosion Inhibitors

Anodic Corrosion Inhibitors
  Molybdate
  Nitrite
  Orthophosphate
  Silicate
Mainly Cathodic Corrosion Inhibitors
  Bicarbonate
  Polyphosphate
  Phosphonate
  Zinc
  Polysilicate
General
  Soluble oils
  Other organics, such as azole or carboxylate

potential occurs at the unprotected anode sites. This causes severe localized (or pitting) attack.

Cathodic corrosion inhibitors form a protective film on the cathode. These inhibitors reduce the corrosion rate in direct proportion to the reduction of the cathodic area.

General corrosion inhibitors protect by forming a film on all metal surfaces whether anodic or cathodic.

Table 3 lists typical corrosion inhibitors. The most important factor in an effective corrosion inhibition program is the consistent control of both the corrosion inhibition chemicals and the key water characteristics. No program will work without controlling these factors.

Cathodic Protection. Sacrificial anodes reduce galvanic attack by providing a metal (usually zinc, but sometimes magnesium) that is higher on the galvanic series than either of the two metals that are coupled together. The sacrificial anode thereby becomes anodic to both metals and supplies electrons to these cathodic surfaces. Proper design and placement of these anodes are important. When properly used, they can reduce loss of steel from the tube sheet of exchangers using copper tubes. Sacrificial anodes have helped supplement chemical programs in many cooling water and process water systems.

Impressed-current protection is a similar corrosion control technique that reverses the corrosion cell's normal current flow by impressing a stronger current of opposite polarity. Direct current is applied to an anode—inert (platinum, graphite) or expendable (aluminum, cast iron)—reversing the galvanic flow and converting the steel from a corroding anode to a protective cathode. The method is very effective in protecting essential equipment such as elevated water storage tanks, steel tanks, or softeners.

White Rust on Galvanized Steel Cooling Towers

White rust is a zinc corrosion product that forms on galvanized surfaces. It appears as a white, waxy or fluffy deposit composed of loosely adhering zinc carbonate. The loose crystal structure allows continued access of the corrosive water to exposed zinc. Unusually rapid corrosion of galvanized steel, as evidenced by white rust, can affect galvanized steel cooling towers under certain conditions.

Before chromates in cooling tower water were banned, the common treatment system consisted of chromates for corrosion control and sulfuric acid for scale control. This control method generally has been replaced by alkaline treatment involving scale inhibitors at a higher pH. Alkaline water chemistry is naturally less corrosive to steel and copper, but create an environment where white rust on galvanized steel can occur. Also, some scale prevention programs soften the water to reduce hardness, rather than use acid to reduce alkalinity. The resulting soft water is corrosive to galvanized steel.

Prevention. White rust can be prevented by promoting the formation of a nonporous surface layer of basic zinc carbonate. This barrier layer is formed during a process called **passivation** and

normally protects the galvanized steel for many years. Passivation is best accomplished by controlling pH during initial operation of the cooling tower. Control of the cooling water pH in the range of 7 to 8 for 45 to 60 days usually allows passivation of galvanized surfaces to occur. In addition to pH control, operation with moderate hardness levels of 100 to 300 ppm as $CaCO_3$ and alkalinity levels of 100 to 300 ppm as $CaCO_3$ will promote passivation. Where pH control is not possible, certain phosphate-based inhibitors may help protect galvanized steel. A water treatment company should be consulted for specific formulations.

SCALE CONTROL

Scale is a dense coating of predominantly inorganic material formed from the precipitation of water-soluble constituents. Some common scales are

- Calcium carbonate
- Calcium phosphate
- Magnesium salts
- Silica

The following principal factors determine whether or not a water is scale forming:

- Temperature
- Alkalinity or acidity (pH)
- Amount of scale-forming material present
- Influence of other dissolved materials, which may or may not be scale-forming

As any of these factors changes, scaling tendencies also change. Most salts become more soluble as temperature increases. However, some salts, such as calcium carbonate, become less soluble as temperature increases. Therefore, they often cause deposits at higher temperatures.

A change in pH or alkalinity can greatly affect scale formation. For example, as pH or alkalinity increases, calcium carbonate—the most common scale constituent in cooling systems—decreases in solubility and deposits on surfaces. Some materials, such as silica (SiO_2), are less soluble at lower alkalinities. When the amount of scale-forming material dissolved in water exceeds its saturation point, scale may result. In addition, other dissolved solids may influence scale-forming tendencies. In general, a higher level of scale-forming dissolved solids results in a greater chance for scale formation. Indices such as the Langelier Saturation Index (Langelier 1936) and the Ryznar Stability Index (Ryznar 1944) can be useful tools to predict the calcium carbonate scaling tendency of water. These indices are calculated using the pH, alkalinity, calcium hardness, temperature, and total dissolved solids of the water, and indicate whether the water will favor precipitating or dissolving of calcium carbonate.

Methods used to control scale formation include

- Limit the concentration of scale-forming minerals by controlling cycles of concentration or by removing the minerals before they enter the system (see the section on External Treatments later in this section). **Cycles of concentration** is the ratio of makeup rate to the sum of blowdown and drift rates. The cycles of concentration can be monitored by calculating the ratio of chloride ion, which is highly soluble, in the system water to that in the makeup water.
- Make mechanical changes in the system to reduce the chances for scale formation. Increased water flow and exchangers with larger surface areas are examples.
- Feed acid to keep the common scale forming minerals (e.g., calcium carbonate) dissolved.
- Treat with chemicals designed to prevent scale. Chemical scale inhibitors work by the following mechanisms:

1. **Threshold inhibition chemicals** prevent scale formation by keeping the scale forming minerals in solution and not allowing a deposit to form. Threshold inhibitors include organic phosphates, polyphosphates, and polymeric compounds.
2. **Scale conditioners** modify the crystal structure of scale, creating a bulky, transportable sludge instead of a hard deposit. Scale conditioners include lignins, tannins, and polymeric compounds.

Nonchemical Methods

Equipment based on magnetic, electromagnetic, or electrostatic technology has been used for scale control in boiler water, cooling water, and other process applications.

Magnetic systems are designed to cause scale-forming minerals to precipitate in a low-temperature area away from heat exchanger surfaces, thus producing nonadherent particles (e.g., aragonite form of calcium carbonate versus the hard, adherent calcite form). The precipitated particles can then be removed by blowdown, mechanical means, or physical flushing.

The objective of **electrostatics** is to prevent scale-forming reactions by imposing a surface charge on dissolved ions that causes them to repel.

Results of side-by-side comparative tests with conventional water treatment have been mixed. A Federal Technology Alert report regarding these technologies (DOE 1998) stresses that success of the application depends largely on the experience of the installer. The report includes a discussion of the potential benefits achieved and the necessary precautions to consider when applying these systems.

ASHRAE Research Project RP-1155 (Cho 2002) studied physical water treatment (PWT). For this study, a PWT device was defined as a nonchemical method of water treatment for scale prevention or mitigation. Bulk precipitation was proposed as the mechanism of scale prevention. Three different devices described as permanent magnets, a solenoid coil device, and a high-voltage electrode were tested under laboratory conditions. Fouling resistance data obtained in a heat transfer test section supported the benefit of all three devices when configured in optimum conditions.

External Treatments

Minerals may also be removed by various external pretreatment methods such as reverse osmosis and ion exchange. Zeolite softening, demineralization, and dealkalization are examples of ion exchange processes.

BIOLOGICAL GROWTH CONTROL

Biological growth (algae, bacteria, and fungi) can interfere with a cooling operation due to fouling or corrosion, and may present a health hazard if present in aerosols produced by the equipment. Heating equipment operates above normal biological limits and therefore has fewer microbial problems. When considering biological growth in a cooling system, it is important to distinguish between free-living planktonic organisms and sessile (attached) organisms. Sessile organisms cause the majority of the problems, though they may have entered and multiplied as planktonic organisms.

Biological fouling can be caused by a wide variety of organisms that produce biofilm and slime masses. Slimes can be formed by bacteria, algae, yeasts, or molds and frequently consist of a mixture of these organisms combined with organic and inorganic debris. Organisms such as barnacles and mussels may cause fouling when river, estuarine, or sea water is used. Biological fouling can significantly reduce the efficiency of cooling by reducing heat transfer, increasing back pressure on recirculation pumps, disrupting flow patterns over cooling media, plugging heat exchangers, and blocking distribution systems. In extreme cases the additional mass of slime has caused the cooling media to collapse.

Microorganisms can dramatically enhance, accelerate or, in some cases, initiate localized corrosion (pitting). Microorganisms can influence localized corrosion directly by their metabolism or indirectly by the deposits they form. Indirect influence may not be mediated by simply killing the microorganisms; deposit removal is usually necessary, while direct influence can be substantially mediated by inhibiting microorganism metabolism.

Algae use energy from the sun to convert bicarbonate or carbon dioxide into biomass. Masses of algae can block piping, distribution holes, and nozzles. A distribution deck cover, which drastically reduces the sunlight reaching the algae, is one of the most cost-effective control devices for a cooling tower. Biocides are also used to assist in the control of algae.

Algae can also provide nutrients for other microorganisms in the cooling system, increasing the biomass in the water. Bacteria can grow in systems even when nutrient levels are relatively low. Yeasts and fungi are much slower growing than bacteria and find it difficult to compete in bulk waters for the available food. Fungi do thrive in partially wetted and high humidity areas such as the cooling media. Wood-destroying species of fungi can be a major concern for wooden cooling towers as the fungi consume the cellulose and/or lignin in the wood, reducing its structural integrity.

Most waters contain organisms capable of producing biological slime, but optimal conditions for growth are poorly understood. Equipment near nutrient sources or that has process leaks acting as a food source is particularly susceptible to slime formation. Even a thin layer of biofilm significantly reduces heat transfer rates in exchangers.

Control Measures

Eliminating sunlight from wetted surfaces such as distribution troughs, cooling media, and sumps significantly reduces algae growth. Eliminating deadlegs and low flow areas in the piping and the cooling loop reduces biological growth in those areas. Careful selection of materials of construction can remove nutrient sources and environmental niches for growth. Maintaining a high quality makeup water supply with low bacteria counts also helps minimize biological growth. Equipment should also be designed with adequate access for inspection, sampling, and manual cleaning.

Sometimes the effective control of slime and algae requires a combination of mechanical and chemical treatments. For example, when a system already contains a considerable accumulation of slime, a preliminary mechanical cleaning makes the subsequent application of a biocidal chemical more effective in killing the growth and more effective in preventing further growth. A buildup of scale deposits, corrosion product, and sediment in a cooling system also reduces the effectiveness of chemical biocides. Routine manual cleaning of cooling towers, including the use of high level chlorination and a biodispersant (surfactant), helps control Legionella bacteria as well as other microorganisms.

Microbiocides. Chemical biocides used to control biological growth in cooling systems fall into two broad categories: oxidizing and nonoxidizing biocides.

Oxidizing biocides (chlorine, chlorine-yielding compounds, bromine, bromochlorodimethylhydantoin (BCDMH, or BCD), ozone, iodine, and chlorine dioxide) are among the most effective microbiocidal chemicals. However, they are not always appropriate for control in cooling systems with a high organic loading. In air washers, the odor may become offensive; in wooden cooling towers, excessive concentrations of oxidizing biocides can cause delignification; and overdosing of oxidizing biocides may cause corrosion of metallic components. In systems large enough to justify the cost of equipment to control feeding of oxidizing biocides accurately, the application may be safe and economical. The most effective use of oxidizing biocides is to maintain a constant low level residual in the system. However, if halogen-based oxidizing biocides are fed intermittently (slug dosed), a pH near 7 is advantageous because, at this

neutral pH, halogens are present as the hypohalous acid (HOR, where R represents the halogen) form over the hypohalous ion (OR⁻) form. The effectiveness of this shock feeding is enhanced due to the faster killing action of hypohalous acid over that of hypohalous ion. The residual biocide concentration should be tested, using a field test kit, on a routine basis. Most halogenation programs can benefit from the use of dispersants or surfactants (chlorine helpers) to break up microbiological masses.

Chlorine has been the oxidizing biocide of choice for many years, either as chlorine gas or in the liquid form as sodium hypochlorite. Other forms of chlorine, such as powders or pellets, are also available. Use of chlorine gas is declining due to the health and safety concerns involved in handling this material and in part due to environmental pressures concerning the formation of chloramines and trihalomethane.

Bromine is produced either by the reaction of sodium hypochlorite with sodium bromide on site, or by release from pellets. Bromine has certain advantages over chlorine: it is less volatile, and bromamines break down more rapidly than chloramines in the environment. Also, when slug feeding biocide in high pH systems, hypobromous acid may have an advantage because its dissociation constant is lower than that of chlorine. This effect is less important when biocides are fed continuously.

Ozone has several advantages compared to chlorine: it does not produce chloramines or trihalomethane, it breaks down to nontoxic compounds rapidly in the environment, it controls biofilm better, and it requires significantly less chemical handling. The use of ozone-generating equipment in an enclosed space however, requires care be taken to protect operators from the toxic gas. Also, research by ASHRAE has shown that ozone is only marginally effective as a scale and corrosion inhibitor (Gan et al. 1996, Nasrazadani and Chao 1996).

Water conditions should be reviewed to determine the need for scale and corrosion inhibitors and then, as with all oxidizing biocides, inhibitor chemicals should be carefully selected to ensure compatibility. To maximize the biocidal performance of the ozone, the injection equipment should be designed to provide adequate contact of the ozone with the circulating water. In larger systems, care should be taken to ensure that the ozone is not depleted before the water has circulated through the entire system.

Iodine is provided in pelletized form, often from a rechargeable cartridge. Iodine is a relatively expensive chemical for use on cooling towers and is probably only suitable for use on smaller systems.

Nonoxidizing Biocides. When selecting a nonoxidizing microbiocide, the pH of the circulating water and the chemical compatibility with the corrosion and/or scale inhibitor product must be considered. The following list, while not exhaustive, identifies some of these products:

- Quaternary ammonium compounds
- Methylene bis(thiocyanate) (MBT)
- Isothiazolones
- Thiadiazine thione
- Dithiocarbamates
- Decyl thioethanamine (DTEA)
- Glutaraldehyde
- Dodecylguanidine
- Benzotriazole
- Tetrakis(hydroxymethyl)phosphonium sulfate (THPS)
- Dibromo-nitrilopropionamide (DBNPA)
- Bromo-nitropropane-diol
- Bromo-nitrostyrene (BNS)
- Proprietary blends

The manner in which nonoxidizing biocides are fed is important. Sometimes the continuous feeding of low dosages is neither effective nor economical. Slug feeding large concentrations to achieve a toxic level of the chemical in the water for a sufficient time to kill the

organisms present can show better results. Water blowdown rate and biocide hydrolysis (chemical degradation) rate affect the required dosage. The hydrolysis rate of the biocide is affected by the type of biocide, along with the temperature and pH of the system water. Dosage rates are proportional to system volume; dosage concentrations should be sufficient to ensure that the contact time of the biocide is long enough to obtain a high kill rate of microorganisms before the minimum inhibitory concentration of the biocide is reached. The period between nonoxidizing biocide additions should be based on the system half life, with sequential additions timed to prevent regrowth of bacteria in the water.

Handling Microbiocides. All microbiocides must be handled with care to ensure personal safety. In the United States, cooling water microbiocides are approved and regulated through the EPA and, by law, must be handled in accordance with labeled instructions. Maintenance staff handling the biocides should read the material safety data sheets and be provided with all the appropriate safety equipment to handle the substance. Automatic feed systems should be used that minimize and eliminate the handling of biocides by maintenance personnel.

Other Biocides. Ultraviolet irradiation deactivates the microorganisms as the water passes through a quartz tube. The intensity of the light and thorough contact with the water are critical in obtaining a satisfactory kill of microorganisms. Suspended solids in the water or deposits on the quartz tube significantly reduce the effectiveness of this treatment method. Therefore, a filter is often installed upstream of the lamp to minimize these problems. Because the ultraviolet light leaves no residual material in the water, sessile organisms and organisms that do not pass the light source are not affected by the ultraviolet treatment. Ultraviolet irradiation may be effective on humidifiers and air washers where the application of biocidal chemicals is unacceptable and where 100% of the recirculating water passes the lamp. Ultraviolet irradiation is less effective where all the microorganisms cannot be exposed to the treatment, such as in cooling towers. Ultraviolet lamps require replacement after approximately every 8000 h of operation.

Metallic ions, namely copper and silver, effectively control microbial populations under very specific circumstances. Either singularly or in combination, copper and silver ions are released into the water via electrochemical means to generate 1 to 2 ppm of copper and/or 0.5 to 1.0 ppm of silver. The ions assist in the control of bacterial populations in the presence of a free chlorine residual of at least 0.2 ppm. Copper, in particular, effectively controls algae.

Liu et al. (1994) reported control of *Legionella pneumophila* bacteria in a hospital hot water supply using copper-silver ionization. In this case, *Legionella* colonization decreased significantly when copper and silver concentrations exceeded 0.4 and 0.04 ppm, respectively. Also, residual disinfection prevented *Legionella* colonization for two months after the copper-silver unit was inactivated.

Significant limitations exist in the use of copper and silver ion for cooling systems. Many states are restricting the discharge of these ions to surface waters, and if the pH of the system water rises above 7.8, the efficacy of the treatment is significantly reduced. Systems that have steel or aluminum heat exchangers should not be treated by this method, as the potential for the deposition of the copper ion and subsequent galvanic corrosion is significant.

Legionnaires' Disease

Like other living things, *Legionella pneumophila*, the bacterium that causes Legionnaires' disease (legionellosis), requires moisture for survival. *Legionella* bacteria are widely distributed in natural water systems and are present in many drinking water supplies. Potable hot water systems between 80 and 120°F, cooling towers, certain types of humidifiers, evaporative condensers, whirlpools and spas, and the various components of air conditioners are considered to be amplifiers. These bacteria are killed in a matter of minutes when exposed to temperatures above 140°F.

Legionellosis can be acquired by inhalation of *Legionella* organisms in aerosols. Aerosols can be produced by cooling towers, evaporative condensers, decorative fountains, showers, and misters. It has been reported that the aerosol from cooling towers can be transmitted over a distance of up to 2 miles. If air inlet ducts of nearby air conditioners draw the aerosol from contaminated cooling towers into the building, the air distribution system itself can transmit the disease. When an outbreak of Legionnaires' disease occurs, cooling towers are often the suspected source. However, other water systems may produce an aerosol and should not be neglected. Amplification of *Legionella* within protozoans has been demonstrated, and *Legionella* bacteria are thought to be protected from biocides while growing intracellularly. Amplification of *Legionella* bacteria in biofilm and slime masses has been shown by a number of researchers. Microbial control programs should consider the effectiveness of the products against slimes as part of the *Legionella* control program.

Humidifiers. Units that generate a water aerosol for humidity control can become amplifiers of bacteria if their reservoirs are poorly maintained. Manufacturers' recommendations on cleaning and maintenance should be followed closely. Steam humidifiers should not pose a bacterial problem because the steam does not contain bacteria.

Whirlpools and Spas. These units pose a potential hazard to users if not properly maintained. The complexity of some units makes cleaning difficult, so a firm that specializes in cleaning these devices may need to be hired. Manufacturers' instructions should be followed carefully.

Decorative Fountains. If these systems become contaminated, *Legionella* may multiply and pose a hazard to those nearby. The recirculating water should be kept clean and clear with proper filtration. Continuous chlorination or use of another biocide with EPA approval for decorative fountains is recommended. Indoor decorative fountains with ponds containing fish and other aquatic life cannot be chlorinated or treated; steps should be taken to ensure that water does not become airborne via sprays or cascading waterfalls.

Roof Ponds. These are used to lower the roof temperature and thus the demand on the air conditioning. If contaminated, such ponds can pose a risk to the staff and general public. Roof ponds should be monitored and treated in the same manner as recirculating cooling water systems (see the section on Selection of Water Treatment).

Safety Showers. Safety showers are mandated for safety, but they are used infrequently. Standing reservoirs of nonsterile water at room temperature should be avoided. A preventative maintenance program that includes flushing is suggested.

Vegetable Misters or Sprays. Although an older-style ultrasonic mist machine has been implicated in at least one case of this disease, once-through cool-water sprayers, (directly connected to a cold, potable water line with no reservoir) do not appear to be a problem.

Machine Shop Cooling. Water used in machining operations may be mixed with oil or other ingredients to improve cooling and cutting efficiency. It is typically stored in holding tanks that are subject to bacterial contamination, including by *Legionella*. Bacterial activity should be monitored and controlled.

Ice-Making Machines. While *Legionella* bacteria are not likely to amplify in this cold environment, bacterial amplification can occur prior to freezing the water. Graman et al. (1997) described a case in which *Legionella* were presumed to have been transmitted by aspiration of ice or ice water from an ice machine.

Prevention and Control. The *Legionella* count required to cause illness has not been firmly established because many factors are involved, including (1) virulence and number of *Legionella* in the air, (2) rate at which the aerosol dries, (3) wind direction, and (4) susceptibility to the disease of the person breathing the air. The organism is often found in sites not associated with an outbreak of the disease. It has been shown that it is feasible to operate cooling

systems with *Legionella* bacteria below the limit of detection and that the only method to prove that a system is operating at these levels is to specifically test for *Legionella* bacteria, rather than to infer from total bacteria count measurements.

Periodic monitoring of circulating water for total bacteria count and *Legionella* count can be accomplished using culture methods. However, routine culturing of samples from building water systems may not yield an accurate prediction of the risk of *Legionella* transmission. Monitoring system cleanliness and using a microbial control agent that has proven efficacy or is generally regarded as effective in controlling *Legionella* populations are also important. Other measures to decrease risk include optimizing cooling tower design to minimize drift, eliminating deadlegs or low flow areas, selecting materials that do not promote the growth of *Legionella*, and locating the tower so that drift is not injected into the air handlers. The *Legionellosis Position Statement*, an ASHRAE Position Paper (1998) has further information on this topic.

SUSPENDED SOLIDS AND DEPOSITATION CONTROL

Mechanical Filtration

Strainers, filters, and separators may be used to reduce suspended solids to an acceptable low level. Generally, if the screen is 200 mesh, equivalent to about 0.003 in., it is called a strainer; if it is finer than 200 mesh, it is called a filter.

Strainers. A strainer is a closed vessel with a cleanable screen designed to remove and retain foreign particles down to 0.001 in. diameter from various flowing fluids. Strainers extract material that is not wanted in the fluid, and allow saving the extracted product if it is valuable. Strainers are available as single-basket or duplex units, manual or automatic cleaning units, and may be made of cast iron, bronze, stainless steel, copper-nickel alloys, or plastic. Magnetic inserts are available where microscopic iron or steel particles are present in the fluid.

Cartridge Filters. These are typically used as final filters to remove nearly all suspended particles from about 0.004 in. down to 0.00004 in. or less. Cartridge filters are typically disposable (i.e., once plugged, they must be replaced). The frequency of replacement, and thus the economical feasibility of their use, depends on the concentration of suspended solids in the fluid, the size of the smallest particles to be removed, and the removal efficiency of the cartridge filter selected.

In general, cartridge filters are favored in systems where contamination levels are less than 0.01% by mass (< 100 ppm). They are available in many different materials of construction and configurations. Filter media materials include yarns, felts, papers, nonwoven materials, resin-bonded fabric, woven wire cloths, sintered metal, and ceramic structures. The standard configuration is a cylinder with an overall length of approximately 10 in., an outside diameter of approximately 2.5 to 2.75 in., and an inside diameter of about 1 to 1.5 in., where the filtered fluid collects in the perforated internal core. Overall lengths from 4 to 40 in. are readily available.

Cartridges made of yarns, resin-bonded, or melt-blown fibers normally have a structure that increases in density towards the center. These depth-type filters capture particles throughout the total media thickness. Thin media, such as pleated paper (membrane types), have a narrow pore size distribution design to capture particles at or near the surface of the filter. Surface-type filters can normally handle higher flow rates and provide higher removal efficiency than equivalent depth filters. Cartridge filters are rated according to manufacturers' guidelines. Surface-type filters have an absolute rating, while depth-type filters have a nominal rating that reflects their general classification function. Higher efficiency melt-blown depth filters are available with absolute ratings as needed.

Sand Filters. A downflow filter is used to remove suspended solids from a water stream. The degree of suspended solids removal

depends on the combinations and grades of the medium being used in the vessel. During the filtration mode, water enters the top of the filter vessel. After passing through a flow impingement plate, it enters the quiescent (calm) freeboard area above the medium.

In multimedia downflow vessels, various grain sizes and types of media are used to filter the water. This design increases the suspended solids holding capacity of the system, which in turn increases the backwashing interval. Multimedia vessels might also be used for low suspended solids applications, where chemical additives are required. In the multimedia vessel, the fluid enters the top layer of anthracite media, which has an effective size of 0.04 in. This relatively coarse layer removes the larger suspended particles, a substantial portion of the smaller particles, and small quantities of free oil. Flow continues down through the next layer of fine garnet material, which has an effective size of 0.012 in. A more finely divided range of suspended solids is removed in this polishing layer. The fluid continues into the final layer, a coarse garnet material that has an effective size of 0.08 in. Contained in this layer is the header/lateral assembly that collects the filtered water.

When the vessel has retained enough suspended solids to develop a substantial pressure drop, the unit must be backwashed either manually or automatically by reversing the direction of flow. This operation removes the accumulated solids out through the top of the vessel.

Centrifugal-Gravity Separators. In this type of separator, liquids/solids enter the unit tangentially, which sets up a circular flow. Liquids/solids are drawn through tangential slots and accelerated into the separation chamber. Centrifugal action tosses the particles heavier than the liquid to the perimeter of the separation chamber. Solids gently drop along the perimeter and into the separator's quiescent collection chamber. Solids-free liquid is drawn into the separator's vortex (low-pressure area) and up through the separator's outlet. Solids are either purged periodically or continuously bled from the separator by either a manual or automatic valve system.

Bag Type Filters. These filters are composed of a bag of mesh or felt supported by a removable perforated metal basket, placed in a closed housing with an inlet and outlet. The housing is a welded, tubular pressure vessel with a hinged cover on top for access to the bag and basket. Housings are made of carbon or stainless steel. The inlet can be in the cover, in the side (above the bag), or in the bottom (and internally piped to the bag). The side inlet is the simplest type. In any case, the liquid enters the top of the bag. The outlet is located at the bottom of the side (below the bag). Pipe connections can be threaded or flanged. Single-basket housings can handle up to 220 gpm, multibaskets up to 3500 gpm.

The support basket is usually of 304 stainless steel perforated with 1/8 in. holes. (Heavy wire mesh baskets also exist.) The baskets can be lined with fine wire mesh and used by themselves as strainers, without adding a filter bag. Some manufacturers offer a second, inner basket (and bag) that fits inside the primary basket. This provides for two-stage filtering: first a coarse filtering stage, then a finer one. The benefits are longer service time and possible elimination of a second housing to accomplish the same function.

The filter bags are made of many materials (cotton, nylon, polypropylene, and polyester) with a range of ratings from 0.00004 to 0.033 in. Most common are felted materials because of their depth-filtering quality, which provides high dirt-loading capability, and their fine pores. Mesh bags are generally coarser, but are reusable and, therefore, less costly. The bags have a metal ring sewn into their opening; this holds the bag open and seats it on top of the basket rim.

In operation, the liquid enters the bag from above, flows out through the basket, and exits the housing cleaned of particulate down to the desired size. The contaminant is trapped inside the bag, making it easy to remove without spilling any downstream.

Special Methods. Localized areas frequently can be protected by special methods. Thus, pump-packing glands or mechanical

shaft seals can be protected by fresh water makeup or by circulating water from the pump casing through a cyclone separator or filter, then into the lubricating chamber.

In smaller equipment, a good dirt-control measure is to install backflush connections and shutoff valves on all condensers and heat exchangers so that accumulated settled dirt can be removed by backflushing with makeup water or detergent solutions. These connections can also be used for acid cleaning to remove calcium carbonate scale.

In specifying filtration systems, third-party testing by a qualified university or private test agency should be requested. The test report documentation should include a description of methods, piping diagrams, performance data, and certification.

Filters described in this section may also be used where industrial process cooling water is involved. For this type of service, consultation with the filtration equipment manufacturer is essential to ensure proper application.

START-UP AND SHUTDOWN OF COOLING TOWER SYSTEMS

The following guidelines are for start-up (or recommissioning) and shutdown of cooling tower systems:

Start-Up and Recommissioning for Drained Systems

- Clean all debris, such as leaves and dirt from the cooling tower.
- Close building air intakes in the area of the cooling tower to prevent entrainment of biocide and biological aerosols in the building air handling systems.
- Fill the system with water. While operating the condensing water pump(s) and *prior to operating the cooling tower fans*, execute one of the following two biocidal treatment programs:

  1. Resume treatment with the biocide that had been used prior to shutdown. Use the services of the water treatment supplier. Maintain the maximum recommended biocide residual (for the specific biocide) for a period sufficient to bring the system under good biological control (residual and time varies with the biocide).
  2. Treat the system with sodium hypochlorite at a level of 4 to 5 ppm free chlorine residual at a pH of 7.0 to 7.6. The residual level of free chlorine must be held at 4 to 5 ppm for 6 h. Commercially available test kits can be used to measure the residual of free chlorine.

- Once one of the two biocidal treatment programs has been successfully completed, turn on the fan and the put the system in service. The standard water treatment program (including biocidal treatment) should be resumed at this time.

Start-Up and Recommissioning for Undrained (Stagnant) Systems

- Remove accessible solid debris from bulk water storage vessel.
- Close building air intakes in the area of the cooling tower to prevent entrainment of biocide and biological aerosols in the building air handlers.
- Perform one of the two biocide pretreatment procedures (described in the section on Start-Up for Drained Systems) directly to the bulk water storage vessel (cooling tower sump, draindown tank, etc.). *Do not circulate stagnant bulk cooling water over cooling tower fill or operate cooling tower fans during pretreatment.*
- Stagnant cooling water may be circulated with condenser water pumps if tower fill is bypassed. Otherwise, add approved biocide directly to the bulk water source and mix with manual or sidestream flow methods. Take care to prevent the creation of aerosol spray from the stagnant cooling water from any point in the cooling water system.
- When one of the two biocidal pretreatments has been successfully completed, the cooling water should be circulated over the tower

fill. If biocide residual is maintained at a satisfactory level for at least 6 h, the cooling tower fans may then be operated safely.

Shutdown

When the system is to be shut down for an extended period, the entire system (cooling tower, system piping, heat exchangers, etc.) should be flushed and drained using the following procedure:

- Add a dispersant and biocide to the system and recirculate for 12 to 24 h. Confer with a water treatment consultant for suitable chemicals and dosage levels.
- Shut down pumps and completely drain all water distribution piping and headers, as well as the cooling loop. Remove water and debris from dead heads and low areas in the piping, which may not have completely drained.
- Rinse silt and debris from the sump. Pay special attention to corners and crevices. Add a mild solution of detergent and disinfectant to the sump and rinse. If the sump does not completely drain, pump out the remaining water and residue.
- If the equipment cannot be completely drained and is exposed to cold temperatures, freeze protection may be required.

SELECTION OF WATER TREATMENT

As discussed in the previous sections, many methods are available to prevent or correct water-caused problems. The selection of the proper water treatment method, and the chemicals and equipment necessary to apply that method, depends on many factors. The chemical characteristics of the water, which change with the operation of the equipment, are important. Other factors contributing to the selection of proper water treatment are

- Economics
- Chemistry control mechanisms
- Dynamics of the operating system
- Design of major components (e.g., the cooling tower or boiler)
- Number of operators available
- Training and qualifications of personnel
- Preventive maintenance program

Once-Through Systems

Economics is an overriding concern in treating water for once-through systems (in which a very large volume of water passes through the system only once). Protection can be obtained with relatively little treatment per unit mass of water because the water does not change significantly in composition while passing through equipment. However, the quantity of water to be treated is usually so large that any treatment other than simple filtration or the addition of a few parts per million of a polyphosphate, silicate, or other inexpensive chemical may not be practical or affordable. Intermittent treatment with polyelectrolytes can help maintain clean conditions when the cooling water is sediment-laden. In such systems, it is generally less expensive to invest more in corrosion-resistant construction materials than to attempt to treat the water.

Open Recirculating Systems

In an open recirculating system with chemical treatment, more chemical must be present because the water composition changes significantly by evaporation. Corrosive and scaling constituents are concentrated. However, treatment chemicals also concentrate by evaporation; therefore, after the initial dosage, only moderate dosages maintain the higher level of treatment needed. The selection of a water treatment program for an open recirculating system depends on the following major factors:

- Economics
- Water quality
- Performance criteria (e.g., corrosion rate, bacteria count, etc.)
- System metallurgy
- Available staffing

- Automation capabilities
- Environmental requirements
- Water treatment supplier (some technologies are superior to others in terms of economics, ease of use, safety, and impact on the environment)

An open recirculating system is typically treated with a scale inhibitor, corrosion inhibitor, oxidizing biocide, nonoxidizing biocide, and possibly a dispersant. The exact treatment program depends on the previously mentioned conditions.

A water treatment control scheme for a cooling tower might include

- Chemistry and cycles of concentration control using a conductivity controller
- Alkalinity control using automatic injection of sulfuric acid based on pH
- Scale control using contacting water meters, proportional feed, or traced control technology
- Oxidizing biocide control using an ORP (oxidation-reduction potential) controller
- Nonoxidizing biocide control using timers and pump systems

Air Washers and Sprayed Coil Units

A water treatment program for an air washer or a sprayed coil unit is usually complex and depends on the purpose and function of the system. Some systems, such as sprayed coils in office buildings, are used primarily to control the temperature and humidity. Other systems are intended to remove dust, oil vapor, and other airborne contaminants from an airstream. Unless the water is properly treated, the fouling characteristics of the contaminants removed from the air can cause operating problems.

Scale control is important in air washers or sprayed coils providing humidification. The minerals in the water may become concentrated (by evaporation) enough to cause problems. Inhibitor/dispersant treatment commonly used in cooling towers are often used in air washers to control scale formation and corrosion.

Suitable dispersants and surfactants are often needed to control oil and dust removed from the airstream. The type of dispersant depends on the nature of the contaminant and the degree of contamination. For maximum operating efficiency, dispersants should produce minimal amounts of foam.

Control of slime and bacterial growth is also necessary in the treatment of air washers and sprayed coils. The potential for biological growth is enhanced, especially if the water contains contaminants that are nutrients for the microorganisms. Due to variations in conditions and applications of air-washing installations and the possibility of toxicity problems, individual treatment options should be discussed with water treatment experts before a program is chosen. All microbiocides applied in air washers must have specific regulatory approval.

Ice Machines

Lime scale formation, cloudy or "milky" ice, objectionable taste and odor, and sediment are the most frequently encountered water problems in ice machines. Lime scale formation is probably the most serious problem because it interferes with the harvest cycle by forming on the freezing surfaces, preventing the smooth release of ice from the surface to the harvest bin.

Scale is caused by dissolved minerals in the water. Water freezes in a pure state and dissolved minerals concentrate in the unfrozen water; some eventually deposit on the machine's freezing surfaces as scale. As shown in Table 4, the probability of scale formation in an ice machine varies directly with the concentrations of carbonate and bicarbonate in the water circulating in the machine.

Dirty or scaled-up ice makers should be thoroughly cleaned before the water treatment program is started. Water distributor

Table 4   Amount of Scale in an Ice Machine

Total Alkalinity as Bicarbonate, ppm	Hardness as Calcium Carbonate, ppm			
	0 to 49	**50 to 99**	**100 to 199**	**200 and up**
0 to 49	None	Very light	Very light	Very light
50 to 99	Very light	Moderate	Moderate	Moderate
100 to 199	Very light	Troublesome	Troublesome	Heavy
200 and up	Very light	Troublesome	Heavy	Very heavy

holes should be cleared, and all loose sediment and other material should be flushed from the system. Existing scale can be removed by circulating an acid solution through the system.

Slowly soluble food-grade polyphosphates inhibit scale formation on freezing surfaces during normal operation by keeping hardness in solution. Although polyphosphates can inhibit lime scale in the ice-making section and help prevent sludge deposits of loose particles of lime scale in the sump, they do not eliminate the soft, milky, or white ice caused by a high concentration of dissolved minerals in the water.

Even with proper chemical treatment, recirculating water having a mineral content above 500 to 1000 ppm cannot produce clear ice. Increasing bleed off or reducing the thickness of the ice slab or the size of the cubes may mitigate the problem. However, demineralizing or distillation equipment is usually needed to prevent white ice production.

Another problem frequently encountered with ice machines is objectionable taste or odor. When water containing a material having an offensive taste or odor is used in an ice machine, the taste or odor is trapped in the ice. An activated carbon filter on the makeup water line can remove the objectionable material from the water. Carbon filters must be serviced or replaced regularly to avoid organic buildup in the carbon bed.

Occasionally, slime growth causes an odor problem in an ice machine. This problem can be controlled by regularly cleaning the machine with a food-grade acid. If slime deposits persist, sterilization of the ice machine may be helpful.

Feedwater often contains suspended solids such as mud, rust, silt, and dirt. To remove these contaminants, a sediment filter of appropriate size can be installed in the feed lines.

Closed Recirculating Systems

In a closed recirculating system, water composition remains fairly constant with very little loss of either water or treatment chemical. Closed systems are often defined as those requiring less than 5% makeup per year. The need for water treatment in such systems (i.e., water heating, chilled water, combined cooling and heating, and closed loop condenser water systems) is often ignored based on the rationalization that the total amount of scale from the water initially filling the system would be insufficient to interfere significantly with heat transfer, and that corrosion would not be serious. However, leakage losses are common, and corrosion products can accumulate sufficiently to foul heat transfer surfaces. Therefore, all systems should be adequately treated to control corrosion. Systems with high makeup rates should be treated to control scale as well.

The selection of a treatment program for closed systems should consider the following factors:

- Economics
- System metallurgy
- Operating conditions
- Makeup rate
- System size

Possible treatment technologies include

- Buffered nitrite
- Molybdate

- Silicates
- Polyphosphates
- Oxygen scavengers
- Organic blends

Before new systems are treated, they must be cleaned and flushed. Grease, oil, construction dust, dirt, and mill scale are always present in varying degrees and must be removed from the metallic surfaces to ensure adequate heat transfer and to reduce the opportunity for localized corrosion. Detergent cleaners with organic dispersants are available for proper cleaning and preparation of new closed systems.

Water Heating Systems

Secondary and Low-Temperature. Closed, chilled-water systems that are converted to secondary water heating during winter and primary low-temperature water heating, both of which usually operate in the range of 140 to 250°F, require sufficient inhibitors to control corrosion to less than 0.005 in. per year. Ethylene glycol or propylene glycol may be used as antifreeze in secondary hot water systems. Such glycols are available commercially, with inhibitors such as sodium nitrite, potassium phosphate, and organic inhibitors for nonferrous metals added by the manufacturer. These require no further treatment, but softened water should be used for all filling and makeup requirements. Samples should be checked periodically to ensure that the inhibitor has not been depleted. Analytical services are available from the glycol manufacturers and others for this purpose.

Environment- and High-Temperature. Environment-temperature water heating systems (250 to 350°F) and high-temperature, high-pressure hot water systems (above 350°F) require careful consideration of treatment for corrosion and deposit control. Makeup water for such systems should be demineralized or softened to prevent scale deposits. For corrosion control, oxygen scavengers such as sodium sulfite can be added to remove dissolved oxygen.

Electrode boilers are sometimes used to supply low- or high-temperature hot water. Such systems use heat generated due to the electrical resistance of the water between electrodes. The conductivity of the recirculating water must be in a specific range depending on the voltage used. Treatment of this type of system for corrosion and deposit control varies. In some cases oil-based corrosion inhibitors that do not contribute to the conductivity of the recirculating water are used.

Brine Systems

Systems containing brine, a strong solution of sodium chloride or calcium chloride, must be treated to control corrosion and deposits. Sodium nitrite at a minimum 3000 ppm in calcium brines or 4000 ppm in sodium brines, and a pH between 7.0 and 8.5 should provide adequate protection. Organic inhibitors are available that may provide adequate protection where nitrites cannot be used. Molybdates should not be used with calcium brines because insoluble calcium molybdate will precipitate.

Boiler Systems

Many treatment methods are available for steam-producing boilers; the method selected depends on

- Makeup water quality
- Makeup water quantity (or percentage condensate return)
- Pretreatment equipment
- Boiler operating conditions
- Steam purity requirements
- Economics

Pretreatment for makeup water could consist of

- Water softeners (for removal of calcium and magnesium hardness)
- Deaerators (for removal of dissolved gases; especially oxygen and carbon dioxide)

- Dealkalizers (to remove alkalinity in systems with high makeup rates and high alkalinity makeup water)
- Demineralizers (to remove almost all the hardness, alkalinity, and solids, depending on the application)
- Reverse osmosis (can remove up to 99% of minerals and dissolved solids from the water leaving almost pure H_2O)

Contaminants that are not removed mechanically by pretreatment equipment must be treated chemically. Once in the feedwater, dissolved gases, hardness, and dissolved minerals must be treated to prevent deposition and corrosion. ASME (1994) and ABMA (1995) have published recommended water chemistry limits for boiler water.

Treatment of the boiler water is often determined by the end use of the steam. Treatment regimens may include reduction of alkalinity; hardness removal; silica removal; oxygen reduction; and the feed of scale and corrosion inhibitors, oxygen scavengers, condensate treatment chemicals, and antifoams. These regimens are described in the following paragraphs.

Prevention of Scale. After the feedwater is pretreated, scale is controlled with phosphates, acrylates, polymers, chelates, and coagulation programs. Chelates, polymers, and acrylates work by binding the hardness, thereby preventing precipitation and scale formation. Phosphates and coagulation programs work in combination with sludge conditioners (tannins, lignins, starches, and synthetic polymers) to produce a softened precipitate that is removed by blowdown of the boiler.

Prevention of Corrosion and Oxygen Pitting. While boilers can corrode as the result of low boiler water pH or misuse of certain chemicals, corrosion is primarily caused by oxygen. After mechanical deaeration, boiler feedwater must be treated chemically. Effective deaeration removes most of the dissolved oxygen. (Most properly operating deaerators can remove oxygen down to 0.007 ppm and deaerating heaters can remove oxygen down to 0.04 ppm.) Oxygen scavengers such as catalyzed sodium sulfite and proprietary organic oxygen scavengers should then be fed to react with the residual oxygen in feedwater after deaeration. Oxygen scavengers will not only provide added protection to the boiler but to the steam and condensate system as well. Oxygen at levels as low as 0.005 ppm can cause oxygen pitting in the steam and condensate system if not chemically reduced by oxygen scavengers.

Most of the corrosion damage to boilers and associated equipment occurs during idle periods. The corrosion is caused by the exposure of wet metal to oxygen in the air or water. For this reason, special precautions must be taken to prevent corrosion while boilers are out of service.

Wet Boiler Lay-Up. This is a method of storing boilers full of water so that they can be returned to service. It involves adding extra chemicals (usually something to increase alkalinity, an oxygen scavenger, and a dispersant) to the boiler water. The water level is raised in the idle boiler to eliminate air spaces, and the boiler is kept completely full of treated water. Superheaters require special protection. Nitrogen gas can also be used on airtight boilers to maintain a positive pressure on the boiler, thereby preventing oxygen in-leakage.

Dry Boiler Lay-Up. This method of lay-up is usually for longer boiler outages. It involves draining, cleaning, and drying the boiler. A material that absorbs moisture, such as hydrated lime or silica gel, is placed in trays inside the boiler. The boiler is then sealed carefully to keep out air. Periodic inspection and replacement of the drying chemical are required during long storage periods.

Steam and Condensate Systems

Two problems associated with steam and condensate systems include general corrosion and pitting corrosion. In order to prevent condensate corrosion, the systems must be protected from acidic conditions, which lead to general corrosion, and oxygen, which leads to pitting corrosion. Protection can be by mechanical or chemical means or a combination of both. The following methods are commonly used for condensate system protection.

Protection from General Corrosion

Mechanical Protection. Reduce alkalinity from boiler feedwater to minimize the amount of carbon dioxide in the system. Carbon dioxide reacts with water (condensate) and forms carbonic acid that will corrode condensate system metal. Alkalinity can be reduced by dealkalization, demineralization, and reverse osmosis. Note: In many cases mechanical reduction of alkalinity is not needed due to low alkalinity makeup water and/or feedwater.

Chemical Protection. Use volatile amines, such as morpholine, diethylaminoethanol (DEAE), and cyclohexylamine, to neutralize carbonic acid and keep the condensate pH between 8.0 and 9.0.

Protection from Oxygen Corrosion

Mechanical Protection. Reduce oxygen from all boiler feedwater to prevent oxygen carryover to the steam and condensate system (via mechanical methods and chemical oxygen scavengers).

Chemical Protection. Feed filming amines, such as octadecylamine, to the steam to form a thin, hydrophobic film on the condensate system surfaces.

Chemical Protection. Feed a volatile oxygen scavenger to the steam to scavenge the oxygen.

The need for chemical treatment can be reduced by designing and maintaining tight return systems so that the condensate is returned to the boiler and less makeup is required in the boiler feedwater. The greater the amount of makeup, the more the system requires increased chemical treatment.

TERMINOLOGY

The following terms are commonly used in the water treatment industry as they pertain to corrosion, scale formation and fouling.

Alkalinity. The sum of bicarbonate, carbonate, and hydroxide ions in water. Other ions, such as borate, phosphate, or silicate, can also contribute to alkalinity.

Anion. A negatively charged ion of an electrolyte that migrates toward the anode influenced by an electric potential gradient.

Anode. The electrode of an electrolytic cell at which oxidation occurs.

Biological deposits. Water-formed deposits of biological organisms or the products of their life processes, such as barnacles, algae, or slimes.

Cathode. The electrode of an electrolytic cell at which reduction occurs.

Cation. A positively charged ion of an electrolyte that migrates toward the cathode influenced by an electric potential gradient.

Corrosion. The deterioration of a material, usually a metal, by reaction with its environment.

Corrosivity. The capacity of an environment or environmental factor to bring about destruction of a specific metal by the process of corrosion.

Electrolyte. A solution through which an electric current can flow.

Filtration. Process of passing a liquid through a porous material in such a manner as to remove suspended matter from the liquid.

Galvanic corrosion. Corrosion resulting from the contact of two dissimilar metals in an electrolyte or from the contact of two similar metals in an electrolyte of nonuniform concentration.

Hardness. The sum of the calcium and magnesium ions in water; usually expressed in ppm as $CaCO_3$.

Inhibitor. A chemical substance that reduces the rate of corrosion, scale formation, fouling, or slime production.

Ion. An electrically charged atom or group of atoms.

Passivity. The tendency of a metal to become inactive in a given environment.

pH. The logarithm of the reciprocal of the hydrogen ion concentration of a solution. pH values below 7 are increasingly acidic; those above 7 are increasingly alkaline.

Polarization. The deviation from the open circuit potential of an electrode resulting from the passage of current.

ppm. Parts per million by mass. In water, ppm are essentially the same as milligrams per liter (mg/L); 10,000 ppm (mg/L) = 1%.

Scale. 1. The formation at high temperature of thick corrosion product layers on a metal surface. 2. The precipitation of water-insoluble constituents on a surface.

Sludge. A sedimentary water-formed deposit, either of biological origin or suspended particles from the air.

Tuberculation. The formation over a surface of scattered, knob-like mounds of localized corrosion products.

Water-formed deposit. Any accumulation of insoluble material derived from water or formed by the reaction with water on surfaces in contact with it.

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CHAPTER 49

SERVICE WATER HEATING

WATER HEATING energy use is second only to space conditioning in most residential buildings, and is also significant in many commercial and industrial settings. In some climates and applications, water heating is the largest energy use in a building. Moreover, quick availability of adequate amounts of hot water is an important factor in user satisfaction. Both water and energy waste can be significant in poorly designed service water heating systems: from over- or undersizing pipes and equipment, from poor building layout, and from poor system design and operating strategies. Good service water heating system design and operating practices can often reduce first costs as well as operating costs. The information in this chapter is thus critical for the sustainable design and operation of many buildings.

SYSTEM ELEMENTS

A service water-heating system has (1) a heat energy source, (2) heat transfer equipment, (3) a distribution system, and (4) terminal hot-water usage devices.

Heat energy sources may be (1) fuel combustion; (2) electrical conversion; (3) solar energy; (4) geothermal, air, or other environmental energy; and/or (5) recovered waste heat from sources such as flue gases, ventilation and air-conditioning systems, refrigeration cycles, and process waste discharge.

Heat transfer equipment is direct, indirect, or a combination of the two. For direct equipment, heat is derived from combustion of fuel or direct conversion of electrical energy into heat and is applied within the water-heating equipment. For indirect heat transfer equipment, heat energy is developed from remote heat sources (e.g., boilers; solar energy collection; air, geothermal, or other environmental source; cogeneration; refrigeration; waste heat) and is then transferred to the water in a separate piece of equipment. Storage tanks may be part of or associated with either type of heat transfer equipment.

Distribution systems transport hot water produced by water-heating equipment to terminal hot-water usage devices. Water consumed must be replenished from the building water service main. For locations where constant supply temperatures are desired, circulation piping or a means of heat maintenance must be provided.

Terminal hot-water usage devices are plumbing fixtures and equipment requiring hot water that may have periods of irregular flow, constant flow, and no flow. These patterns and their related water usage vary with different buildings, process applications, and personal preference.

The preparation of this chapter is assigned to TC 6.6, Service Water Heating.

In this chapter, it is assumed that an adequate supply of building service water is available. If this is not the case, alternative strategies such as water accumulation, pressure control, and flow restoration should be considered.

WATER-HEATING TERMINOLOGY

Recovery efficiency. Heat absorbed by the water divided by heat input to heating unit during the period that water temperature is raised from inlet temperature to final temperature (includes heat losses from water heater jacket and/or tank).

Recovery rate. The amount of hot water that a residential water heater can continually produce, usually reported as flow rate in gallons per hour that can be maintained for a specified temperature rise through the water heater.

Fixture unit. A number, on an arbitrarily chosen scale, that expresses the load-producing effects on the system of different kinds of fixtures.

Thermal efficiency. Heat in water flowing from the heater outlet divided by the energy input to the heating unit over a specific period of steady-state conditions (includes heat losses from the water heater jacket and/or tank).

Input efficiency. Heat entering water in the heating device divided by energy input to the heating unit over a specific period of steady-state conditions, or while heating from cold to hot, depending on how stated (steady-state versus average input efficiency); it does not include heat losses from the water heater jacket and/or tank. When used with fossil-fuel-fired equipment, this is commonly called **combustion efficiency**.

Energy factor. The delivered efficiency of a residential water heater when operated as specified in U.S. Department of Energy (DOE) test procedures (DOE 2001). See also ASHRAE *Standard* 118.2.

First-hour rating. An indicator of the maximum amount of hot water a residential water heater can supply in 1 h. This rating is used by the Federal Trade Commission (FTC) for comparative purposes. Because peak draws taken over periods less than 1 h frequently drive residential equipment sizing, first-hour rating alone should not be used for equipment sizing; as for larger systems, storage tank volume and heating rate also play important roles.

Standby loss. As applied to a tank water heater (under test conditions with no water flow), the average hourly energy consumption divided by the average hourly heat energy contained in stored water, expressed as a percent per hour. This can be converted to the average Btu/h energy consumption required to maintain any water/air temperature difference by multiplying the percent by the temperature difference, 8.25 Btu/gal·°F (a nominal specific heat for water), the tank capacity, and then dividing by 100.

Standby loss coefficient. The heat input (in Btu/h·°F) into a storage water heater when operated as specified in U.S. Department of Energy (DOE) test procedures (DOE 2001). This value includes the effect of recovery efficiency.

Hot-water distribution efficiency. Heat contained in the water at points of use divided by heat delivered at the heater outlet at a given flow.

Heater/system efficiency. Heat contained in the water at points of use divided by the heat input to the heating unit at a given flow rate (thermal efficiency times distribution efficiency).

Heat trap. A device to counteract the natural convection of heated water in a vertical pipe. Commercially available heat traps for large equipment are generally 360° loops of tubing; heat traps can also be constructed of pipes connected to the water heater (inlet or outlet) that direct flow downward before connecting to the vertical supply or hot-water distribution system. Tubing or piping heat traps should have a loop diameter or length of downward piping of at least 12 in. Various prefabricated check-valve-like heat traps are available for residential-sized equipment, using balls, flexible flaps, or moving disks.

Overall system efficiency. Heat energy in the water delivered at points of use divided by the total energy supplied to the heater for any selected period.

System standby loss. The amount of heat lost from the water heating system and the auxiliary power consumed during periods of nonuse of service hot water.

SYSTEM PLANNING

The goals of system planning are to (1) size the system properly; (2) optimize system efficiency; and (3) minimize first, operating, and overall life-cycle costs. It is important to design systems so that they perform well from both functional and energy-use perspectives. Flow rate, temperature, and total flow over specific time periods are the primary factors to be determined in the hydraulic and thermal design of a water-heating and piping system. Operating pressures, time of delivery, and water quality are also factors to consider. Separate procedures are used to select water-heating equipment and to design the piping system. However, water-heating equipment sizing and piping system design should be considered together for best system design. Oversized or excessively long piping exacerbates delivery delay and/or energy waste.

Water-heating equipment, storage facilities, and piping should (1) have enough capacity to provide the required hot water while minimizing waste of energy or water and (2) allow economical system installation, maintenance, and operation.

Water-heating equipment types and designs are based on the (1) energy source, (2) application of the developed energy to heat the water, and (3) control method used to deliver the necessary hot water at the required temperature under varying water demand conditions. Application of water-heating equipment within the overall design of the hot-water system is based on (1) location of the equipment within the system, (2) related temperature requirements, (3) volume of water to be used, and (4) flow rate. Consideration of peak demand effects on utilities is also of growing importance.

Energy Sources

The choice of energy source is influenced by equipment type and location. These decisions should be made only after evaluating purchase, installation, operating, and maintenance costs. A life-cycle analysis is highly recommended.

In making energy conservation choices, consult the ANSI/ASHRAE/IESNA *Standards* 90.1 and 90.2, or the sections on Service Water Heating of ANSI/ASHRAE/IESNA *Standard* 100, as well as the section on Design Considerations in this chapter.

WATER-HEATING EQUIPMENT

Gas-Fired Systems

Automatic storage water heaters incorporate the burner(s), storage tank, outer jacket, and controls such as a thermostat in a single unit and have an input-to-storage capacity ratio of less than 4000 Btu/h per gallon.

Automatic instantaneous water heaters are produced in two distinctly different types. Tank-type instantaneous heaters have an input-to-storage capacity ratio of 4000 Btu/h per gallon or more and a thermostat to control energy input to the heater. Water-tube instantaneous heaters have minimal water storage capacity. They usually have a flow switch that controls the burner, and may have a modulating fuel valve that varies fuel flow as water flow changes.

Circulating tank water heaters are classified in two types: (1) automatic, in which the thermostat is located in the water heater, and (2) nonautomatic, in which the thermostat is located within an associated storage tank.

Hot-water supply boilers are capable of providing service hot water. They are typically installed with separate storage tanks and applied as an alternative to circulating tank water heaters. Outside models are wind- and rain-tested. They are available in most of the classifications previously listed.

Direct-vent models are to be installed inside, but are not vented through a conventional chimney or gas vent and do not use ambient air for combustion. They must be installed with the means specified by the equipment manufacturer for venting (typically horizontal) and for supplying combustion air from outside the building.

Direct-fired equipment passes cold water through a stainless steel or other heat exchange medium, which breaks up the water into very small droplets. These droplets then come into direct contact with heat rising from a flame, which heats the water directly.

Residential water-heating equipment is usually the automatic storage type. For industrial and commercial applications, commonly used types of heaters are (1) automatic storage, (2) circulating tank, (3) instantaneous, and (4) hot-water supply boilers.

Installation guidelines for gas-fired water heaters can be found in the National Fuel Gas Code, NFPA *Standard* 54/ANSI *Standard* Z223.1. This code also covers sizing and installation of venting equipment and controls.

Oil-Fired Systems

Oil-fired water heaters are generally the storage tank type. Models with a storage tank of 50 gal or less with an input rating of 105,000 Btu/h or less are usually considered residential models. Commercial models are offered in a wide range of input ratings and tank sizes. There are models available with combination gas/oil burners, which can be switched to burn either fuel, depending on local availability.

Installation guidelines for oil-fired water heaters can be found in NFPA *Standard* 31/ANSI *Standard* Z95.1.

Electric

Electric water heaters are generally the storage type, consisting of a tank with one or more immersion heating elements. The heating elements consist of resistance wire embedded in refractories having good heat conduction properties and electrical insulating values. Heating elements are fitted into a threaded or flanged mounting for insertion into a tank. Thermostats controlling heating elements may be of the immersion or surface-mounted type.

Residential storage tank water heaters range up to 120 gal with input up to 12 kW. They have a primary resistance heating element near the bottom and often a secondary element located in the upper portion of the tank. Each element is controlled by its own

thermostat. In dual-element heaters, the thermostats are usually interlocked so that the lower heating element cannot operate if the top element is operating. Thus, only one heating element operates at a time to limit the current draw.

Commercial storage tank water heaters are available in many combinations of element quantity, wattage, voltage, and storage capacity. Storage tanks may be horizontal or vertical. Compact, low-volume models are used in point-of-use applications to reduce hot-water piping length. Locating the water heater near the point of use makes recirculation loops unnecessary.

Instantaneous electric water heaters are sometimes used in lavatory, hot tub, whirlpool bath, and swimming pool applications. Smaller sizes are commonly used as boosters for dishwasher final rinse applications. Larger sizes are also available, some intended for residential whole-house applications.

Heat pump water heaters (HPWHs) use a vapor-compression refrigeration cycle to extract energy from an air, ground, or water source to heat water. As the HPWH collects heat, it provides a potentially useful cooling effect and, in air-source units, also dehumidifies the air. Some HPWHs have a maximum output temperature of 140°F, although others can deliver much higher temperatures. Where a higher delivery temperature is required than the HPWH can produce, a conventional storage-type or booster water heater downstream of the heat pump storage tank should be used. HPWHs function most efficiently where inlet water temperature is low and source temperature is warm. Systems should be sized to allow high HPWH run time. The effect of HPWH cooling output on the building's energy balance should be considered. Cooling output should be directed to provide occupant comfort and avoid interfering with temperature-sensitive equipment (EPRI 1990).

Demand-controlled water heating can significantly reduce the cost of heating water electrically. Demand controllers operate on the principle that a building's peak electrical demand exists for a short period, during which heated water can be supplied from storage rather than through additional energy applications. Shifting the use of electricity for service water heating from peak demand periods allows water heating at the lowest electric energy cost in many electric rate schedules. The building electrical load must be detected and compared with peak demand data. When the load is below peak, the control device allows the water heater to operate. Some controllers can program deferred loads in steps as capacity is available. The priority sequence may involve each of several banks of elements in (1) a water heater, (2) multiple water heaters, or (3) water-heating and other equipment having a deferrable load, such as pool heating and snow melting. When load controllers are used, hot-water storage must be used.

Electric off-peak storage water heating is a water-heating equipment load management strategy whereby electrical demand to a water-heating system is time-controlled, primarily in relation to the building or utility electrical load profile. This approach may require increased tank storage capacity and/or stored-water temperature to accommodate water use during peak periods.

Sizing recommendations in this chapter apply only to water heating without demand or off-peak control. When demand control devices are used, the storage and recovery rate may need to be increased to supply all the hot water needed during the peak period and during the ensuing recovery period. Manian and Chackeris (1974) include a detailed discussion on load-limited storage heating system design.

Indirect Water Heating

In indirect water heating, the heating medium is steam, hot water, or another fluid that has been heated in a separate generator or boiler. The water heater extracts heat through an external or internal heat exchanger.

When the heating medium is at a higher pressure than the service water, the service water may be contaminated by leakage of the
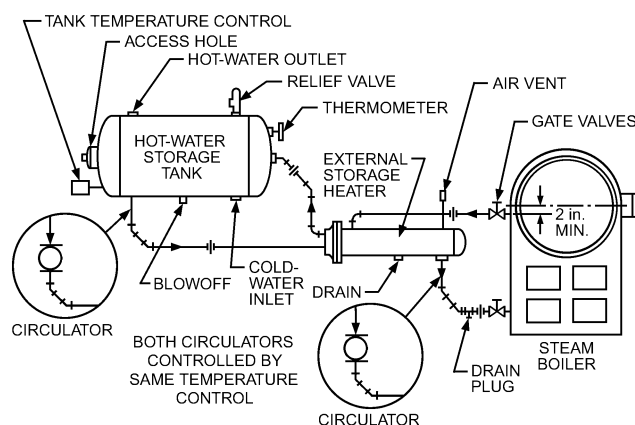
Fig. 1   Indirect, External Storage Water Heater

heating medium through a damaged heat transfer surface. In the United States, some national, state, and local codes require double-wall, vented tubing in indirect water heaters to reduce the possibility of cross-contamination. When the heating medium is at a lower pressure than the service water, other jurisdictions allow single-wall tubing heaters because any leak would be into the heating medium.

If the heating medium is steam, high rates of condensation occur, particularly when a sudden demand causes an inflow of cold water. The steam pipe and condensate return pipes should be of ample size. Condensate may be cooled by preheating the cold-water supply to the heater.

Corrosion is minimized on the heating medium side of the heat exchanger because no makeup water, and hence no oxygen, is brought into that system. The metal temperature of the service water side of the heat exchanger is usually less than that in direct-fired water heaters. This minimizes scale formation from hard water.

Storage water heaters are designed for service conditions where hot-water requirements are not constant (i.e., where a large volume of heated water is held in storage for periods of peak load). The amount of storage required depends on the load's nature and water heater's recovery capacity. An individual tank or several tanks joined by a manifold may be used to provide the required storage.

External storage water heaters are designed for connection to a separate tank (Figure 1). Boiler water circulates through the heater shell, while service water from the storage tank circulates through the tubes and back to the tank. Circulating pumps are usually installed in both the boiler water piping circuit and the circuits between the heat exchanger and the storage tank. Steam can also be used as the heating medium in a similar scheme.

Instantaneous indirect water heaters (tankless coils) are best used for a steady, continuous supply of hot water. In these units, the water is heated as it flows through the tubes. Because the heating medium flows through a shell, the ratio of hot-water volume to heating medium volume is small. As a result, variable flow of the service water causes uncertain temperature control unless a thermostatic mixing valve is used to maintain the hot-water supply to the plumbing fixtures at a more uniform temperature.

Some indirect instantaneous water heaters are located inside a boiler. The boiler is provided with a special opening through which the coil can be inserted. Although the coil can be placed in the steam space above the water line of a steam boiler, it is usually placed below the water line. The water heater transfers heat from the boiler water to the service water. The gross output of the boiler must be sufficient to serve all loads.

Semi-Instantaneous

These water heaters have limited storage to meet the average momentary surges of hot-water demand. They usually consist of a

heating element and control assembly devised for close control of the temperature of the leaving hot water.

Circulating Tank

These water heaters are instantaneous or semi-instantaneous types used with a separate storage tank and a circulating pump. The storage acts as a flywheel to accommodate variations in the demand for hot water.

Blending Injection

These water heaters inject steam or hot water directly into the process or volume of water to be heated. They are often associated with point-of-use applications (e.g., certain types of commercial laundry, food, and process equipment). *Caution*: Cross-contamination of potable water is possible.

Solar

Availability of solar energy at the building site, efficiency and cost of solar collectors, and availability and cost of other fuels determine whether solar energy collection units should be used as a primary heat energy source. Solar energy equipment can also be included to supplement other energy sources and conserve fuel or electrical energy.

The basic elements of a solar water heater include solar collectors, a storage tank, piping, controls, and a transfer medium. The system may use natural or forced circulation. Auxiliary heat energy sources may be added, if needed.

Collector design must allow operation in below-freezing conditions, where applicable. Antifreeze solutions in a separate collector piping circuit arrangement are often used, as are systems that allow water to drain back to heated areas when low temperatures occur. Uniform flow distribution in the collector or bank of collectors and stratification in the storage tank are important for good system performance.

Application of solar water heaters depends on (1) auxiliary energy requirements; (2) collector orientation; (3) temperature of the cold water; (4) general site, climatic, and solar conditions; (5) installation requirements; (6) area of collectors; and (7) amount of storage. Chapter 33 has more detailed design information.

Waste Heat Use

Waste heat recovery can reduce energy cost and the energy requirement of the building heating and service water-heating equipment. Waste heat can be recovered from equipment or processes by using appropriate heat exchangers in the hot gaseous or liquid streams. Heat recovered is frequently used to preheat water entering the service water heater. A conventional water heater is typically required to augment the output of a waste heat recovery device and to provide hot water during periods when the host system is not in operation.

Refrigeration Heat Reclaim

These systems heat water with heat that would otherwise be rejected through a refrigeration, air-conditioning, or heat pump condenser. Refrigeration heat reclaim uses refrigerant-to-water heat exchangers connected to the refrigeration circuit between the compressor and condenser of a host refrigeration or air-conditioning system to extract heat. Water is heated only when the host is operating. Because many simple systems reclaim only superheat energy from the refrigerant, they are often called **desuperheaters**. However, some units are also designed to provide partial or full condensing. The refrigeration heat reclaim heat exchanger is generally of vented, double-wall construction to isolate potable water from refrigerant. Some heat reclaim devices are designed for use with multiple refrigerant circuits. Controls are required to limit high water temperature, prevent low condenser pressure, and provide for freeze protection. Refrigeration systems with higher run time and lower efficiency provide more heat reclaim potential. Most systems are designed with a preheat water storage tank connected in series with a conventional water heater (EPRI 1992). In all installations, care must be taken to prevent inappropriately venting refrigerants.

Combination Heating

A **combo system** provides hot water for both space heating and domestic use. A space-heating coil and a space-cooling coil are often included with the air handler to provide year-round comfort. Combo systems also can use other types of heat exchangers for space heating, such as baseboard convectors or floor heating coils. A method of testing combo systems is given in ASHRAE *Standard* 124. The test procedures allow the calculation of combined annual efficiency (CAE), as well as space- and water-heating efficiency factors. Kweller (1992), Pietsch and Talbert (1989), Pietsch et al. (1994), Subherwal (1986), and Talbert et al. (1992) provide additional design information on these heaters.

DESIGN CONSIDERATIONS

Hot-water system design should consider the following:

- Water heaters of different sizes and insulation may have different standby losses, recovery efficiency, thermal efficiency, or energy factors.
- A distribution system should be properly laid out, sized, and insulated to deliver adequate water quantities at temperatures satisfactory for the uses served. This reduces standby loss and improves hot-water distribution efficiency. Locating fixtures or usage devices close to each other and to the water-heating equipment is particularly important for minimizing piping lengths and diameters, and thus reducing water and energy waste.
- Heat traps between recirculation mains and infrequently used branch lines reduce convection losses to these lines and improve heater/system efficiency. In small residential systems, heat traps can be applied directly to the water heater for the same purpose.
- Controlling circulating pumps to operate only as needed to maintain proper temperature at the end of the main reduces losses on return lines.
- Provision for shutdown of circulators during building vacancy reduces standby losses.

DISTRIBUTION

Piping Material

Traditional piping materials include galvanized steel used with galvanized malleable iron screwed fittings. Copper piping and copper water tube types K, L, or M have been used with brass, bronze, or wrought copper water solder fittings. Legislation or plumbing code changes have banned the use of lead in solders or pipe-jointing compounds in potable water piping because of possible lead contamination of the water supply. See ASHRAE *Standard* 90 series for pipe insulation requirements.

Today, most potable water supplies require treatment before distribution; this may cause the water to become more corrosive. Therefore, depending on the water supply, traditional galvanized steel piping or copper tube may no longer be satisfactory, because of accelerated corrosion. Galvanized steel piping is particularly susceptible to corrosion (1) when hot water is between 140 and 180°F and (2) where repairs have been made using copper tube without a nonmetallic coupling. Note that plumbing can be either piping (relatively thick wall) or tubing (relatively thin wall), although *piping* is used in this chapter for both.

Before selecting any water piping material or system, consult the local code authority. The local water supply authority should also be consulted about any history of water aggressiveness causing failures of any particular material.

Alternative piping materials that may be considered are (1) stainless steel tube and (2) various plastic piping and tubes. Particular care must be taken to ensure that the application meets the design limitations set by the manufacturer and that the correct materials and methods of joining are used. These precautions are easily taken with new projects, but become more difficult during repairs of existing work. Using incompatible piping, fittings, and jointing methods or materials must be avoided, because they can cause severe problems, such as corrosion or leakage caused by differential thermal expansion.

Pipe Sizing

Sizing hot-water supply pipes from a hydraulic (pressure drop) perspective involves the same principles as sizing cold-water supply pipes (see Chapter 36 of the 2005 *ASHRAE Handbook—Fundamentals*). The water distribution system must be correctly sized for the total hot-water system to function properly. Hot-water demand varies with the type of establishment, usage, occupancy, and time of day. The piping system should be able to meet peak demand at an acceptable pressure loss. It is important not to oversize hot-water supply pipes, because this adversely affects system heat loss and overall energy use.

Supply Piping

Table 15, Figures 25 and 26, and manufacturers' specifications for fixtures and appliances can be used to determine hot-water demands. These demands, together with procedures given in Chapter 36 of the 2005 *ASHRAE Handbook—Fundamentals*, are used to size the mains, branches, and risers.

Allowance for pressure drop through the heater should not be overlooked when sizing hot-water distribution systems, particularly where instantaneous water heaters are used and where the available pressure is low.

Pressure Differential

Sizing both cold- and hot-water piping requires that the pressure differential at the point of use of blended hot and cold water be kept to a minimum. This is particularly important for tubs and showers, because sudden changes in flow at fixtures cause discomfort and a possible scalding hazard. Pressure-compensating devices are available.

Piping Heat Loss and Hot-Water Delivery Delays

Good hot-water distribution system layout is very important, for both user satisfaction and energy use. This has become increasingly important with the mandated use of low-flow fixtures, which can cause lengthy delays and increased water waste while waiting for hot water to arrive at fixtures compared to higher-flow designs. In general, it is desirable to put fixtures close to each other and close to the water heater(s) that serve them. This minimizes both the diameter and length of the hot-water piping required. Recent work has shown that energy loss from hot-water piping due to both heat loss and water waste waiting for hot water to arrive at fixtures can be a significant percentage of total water-heating system energy use (Hiller 2005a; Klein 2004a, 2004b, 2004c; Lutz 2005). Energy losses from hot-water distribution systems usually amount to at least 10-20% of total hot-water system energy use in most potable water-heating systems (Hiller 2005a), and are often as high as 50%; losses of over 90% have been found in some installations (Hiller and Miller 2002; Hiller et al. 2002).

Hiller (2005a, 2005b, 2006a, 2006b) measured both piping heat loss and time, water, and energy waste while waiting for hot water to arrive at fixtures. This research measured piping heat loss *UA* factors for several commonly used piping sizes, types, and insulation levels. $UA_{flowing}$ values are a slight function of water flow rate and temperature difference between the hot water and the surroundings.

Table 1 Piping Heat Loss Factors for Foam Insulation with Thermal Conductivity of 0.02 Btu/h·ft²·°F

Nominal Pipe Size, in.	Foam Insulation Thickness, in.	$UA_{zero\ flow}$, Btu/h·ft·°F	High-Value $UA_{flowing}$, Btu/h·ft·°F
1/2 rigid copper	0	0.226	0.36
	0.5	0.128	0.20
	0.75	0.116	0.19
3/4 rigid copper	0	0.388	0.44
	0.5	0.150	0.25
	0.75	0.142	0.24
3/4 PEX-AL-PEX*	0	0.550	0.546
	0.5	0.199	0.199
	0.75	0.158	0.18

Sources: Hiller (2005a, 2005b, 2006b).
*High-density cross-linked polyethylene, aluminum, high-density cross-linked polyethylene multilayer pipe.

However, for many practical calculation purposes, *UA* can be considered constant at the values shown in Table 1.

The *UA* factors of Table 1 are used in Equations (1) to (8) to determine heat loss rates from piping during both flowing and zero-flow (cooldown) conditions, and to find temperature drop while water is flowing through pipe, and pipe temperature at any time during cooldown. Note that piping heat loss and pipe temperature drop are not constant with length under flowing conditions, because the temperature of each successive length of pipe is less than the one before it. The same is true for zero-flow pipe cooldown with respect to time, because the pipe is at a progressively lower temperature at each successive time interval. The result is that pipe temperatures decay inverse-exponentially with length under flowing conditions and with time under cooldown conditions. This is why log-mean temperature difference must be used in heat loss calculations instead of a simple linear temperature difference (Rohsenow and Choi 1961).

Under flowing conditions,

$$Q = mc_p(T_{hot\ in} - T_{hot\ out}) \quad (1)$$

and

$$Q = UA_{flowing}\Delta T_{lm} \quad (2)$$

For water flowing in pipes in a constant-air-temperature environment,

$$\Delta T_{lm} = \frac{[(T_{hot\ in} - T_{air}) - (T_{hot\ out} - T_{air})]}{\ln[(T_{hot\ in} - T_{air})/(T_{hot\ out} - T_{air})]} \quad (3)$$

When $UA_{flowing}$, water flow rate, air temperature, and entering water temperature are known, Equations (1) to (3) can be combined and rearranged to determine pipe-exiting water temperature as follows:

$$T_{hot\ out} = T_{air} + (T_{hot\ in} - T_{air})e^{-\left[\frac{(UA_{flowing})(L_{pipe})}{(mc_{p_{water}})}\right]} \quad (4)$$

where

ΔT_{lm} = log mean temperature difference, °F
Q = heat loss rate, Btu/h
m = water flow rate, lb$_m$/h
c_p = specific heat of water, 1 Btu/lb$_m$·°F
$T_{hot\ in}$ = water temperature entering pipe, °F
$T_{hot\ out}$ = water temperature leaving pipe, °F
$UA_{flowing}$ = flowing heat loss factor per foot of pipe, Btu/h·ft·°F
L_{pipe} = length of hot-water pipe, ft

Note that the quantity $(UA_{flowing})(L_{pipe})/(mc_p)_{water}$ must be non-dimensional, so appropriate units must be used.

Under zero-flow cooldown conditions,

$$Q = (Mc_p)_{w,p,i}(T_{hot\ t_1} - T_{hot\ t_2})/(t_2 - t_1) \qquad (5)$$

$$Q = UA_{zero\text{-}flow}(\Delta T_{lm}) \qquad (6)$$

And for pipe in a constant-air-temperature environment:

$$\Delta T_{lm} = \frac{[(T_{hot\ t_1} - T_{air}) - (T_{hot\ t_2} - T_{air})]}{\ln[(T_{hot\ t_1} - T_{air})/(T_{hot\ t_2} - T_{air})]} \qquad (7)$$

$$T_{hot\ t_2} = T_{air} + (T_{hot\ t_1} - T_{air})e^{-\left[\frac{(UA_{zero\text{-}flow})(t_2 - t_1)}{(Mc_p)_{w,p,i}}\right]} \qquad (8)$$

where

t_1 = initial time
t_2 = final time
Q = average heat loss rate from time t_1 to time t_2, Btu/h
$(Mc_p)_{w,p,i}$ = sum of mass times specific heat for water, pipe, and insulation, Btu/ft·°F
$T_{hot\ t_1}$ = pipe temperature at t_1, °F
$T_{hot\ t_2}$ = pipe temperature at t_2, °F
$UA_{zero\text{-}flow}$ = zero-flow heat loss factor per foot of pipe, Btu/h·ft·°F

Note that the quantity $(UA_{zero\text{-}flow})(t_2 - t_1)/(Mc_p)_{w,p,i}$ must be non-dimensional, so appropriate units must be used.

Pipe temperature at any time during the cooldown process is determined by Equation (8). Total energy lost from piping during zero-flow cooldown is determined by calculating the pipe temperature at time t_2 and multiplying the average heat loss rate between t_1 and t_2 determined by Equation (5) times the duration of the cooldown period $(t_2 - t_1)$. An alternative is to calculate heat loss over short time periods using Equation (6) and sum the results.

Table 2 contains earlier piping heat loss data, and shows computed piping *UA* values based on those data.

Hiller (2005a, 2005b, 2006b) also produced tables of water/energy wasted while waiting for hot water to arrive at fixtures. Waste is a strong function of pipe material, interior finish, diameter, fittings present, flow rate, initial pipe temperature, and entering hot-water temperature. The amount of water wasted to drain is generally an amount greater than pipe volume because temperature of some of the first hot water traveling through the pipe is degraded to below a usable temperature.

Initial flow of hot water into a pipe full of cooler water often does not behave as predicted by steady-state flow theory, because both hot and cold water are flowing simultaneously in the same pipe (a non-steady-state condition). At least three different flow regimes were identified: (1) stratified flow (at low flow rates in horizontal pipes, hot water flows farther along the top side of the pipe than on the bottom side; this can happen even in small-diameter pipes), (2) normal turbulent flow, and (3) plug flow (a sharp hot/cold interface with little mixing of hot and cold water). These flow regimes are important because each causes different amounts of temperature degradation as hot water flows through the pipe.

For detailed information on time, water, and energy waste while waiting for hot water to arrive at fixtures, see Hiller (2005b). Simply summarized here, the amount of water waste can be expressed as the ratio of the actual amount of water (actual flow or AF) wasted while waiting for hot-enough-to-use water to arrive at fixtures (defined as 105°F by Hiller) divided by pipe volume (PV). When the pipe cools below a usable temperature, AF/PV ratios are usually in the range of 1.0 to 2.0, but can go to infinity at low flow rates in long, uninsulated pipe in cold or otherwise adverse (e.g., damp) heat transfer environments. The critical length of pipe at which AF/PV goes to

Table 2   Approximate Heat Loss from Piping at 140°F Inlet, 70°F Ambient

Nominal Size, in.	Bare Copper Tubing, Btu/h·ft	Bare Copper UA, Btu/h·ft·°F	0.5 in. Glass Fiber Insulated Copper Tubing, Btu/h·ft	0.5 in. Glass Fiber Insulated Copper UA, Btu/h·ft·°F
0.75	30	0.43	17.7	0.25
1	38	0.54	20.3	0.29
1.25	45	0.64	23.4	0.33
1.5	53	0.76	25.4	0.36
2	66	0.94	29.6	0.42
2.5	80	1.14	33.8	0.48
3	94	1.34	39.5	0.56
4	120	1.71	48.4	0.69

infinity can be calculated for any flow rate and temperature conditions, using the piping $UA_{flowing}$ factors and Equations (1) to (4).

For preliminary engineering design and energy use calculations, Hiller recommends assuming AF/PV values of 1.25 to 1.75. For more refined analyses, accounting better for temperature effects on AF/PV ratio, the data tables in the original reference should be consulted. More such data on a larger variety of pipe sizes, types, and environments would be beneficial, but are not currently available.

Examples 11 to 14 demonstrate how to use piping heat loss and delivery water waste information to calculate hot-water system energy use.

Hot-Water Recirculation Loops and Return Piping

Hot-water recirculation loops are commonly used where piping lengths are long and hot water is desired immediately at fixtures. In recirculation-loop systems, return piping and a circulation device are provided. Some recirculation-loop systems use buoyancy-driven natural convection forces to circulate flow, but most are equipped with circulating pumps to force water through the piping and back to the water heater, thus keeping water in the piping hot.

The water circulation pump may be controlled by a thermostat (in the return line) set to start and stop the pump over an acceptable temperature range. This thermostat can significantly reduce both heat loss and pumping energy in some applications. An automatic time switch or other control should turn water circulation off when hot water is not required. Other, more advanced circulating pump control schemes, such as on-demand types using manual initiation, flow switches, or occupancy sensors, are also available. Because hot water is corrosive, circulating pumps should be made of corrosion-resistant material.

For small installations, a simplified pump sizing method is to allow 1 gpm for every 20 fixture units in the system, or to allow 0.5 gpm for each 3/4 or 1 in. riser; 1 gpm for each 1 1/4 or 1 1/2 in. riser; and 2 gpm for each riser 2 in. or larger.

Dunn et al. (1959) and Werden and Spielvogel (1969a, 1969b) discuss heat loss calculations for large systems. For larger installations, piping heat losses become significant. A quick method to size the pump and return for larger systems is as follows:

1. Determine total length of all hot-water supply and return piping.
2. Choose an appropriate value for piping heat loss from Tables 1 or 2 or other engineering data (usually supplied by insulation companies, etc.). Multiply this value by the total length of piping involved.

A rough estimation can be made by multiplying the total length of covered pipe by 30 Btu/h·ft or uninsulated pipe by 60 Btu/h·ft. Table 2 gives actual heat losses in pipes at a service water temperature of 140°F and ambient temperature of 70°F. The values of 30 or 60 Btu/h·ft are only recommended for ease in calculation.
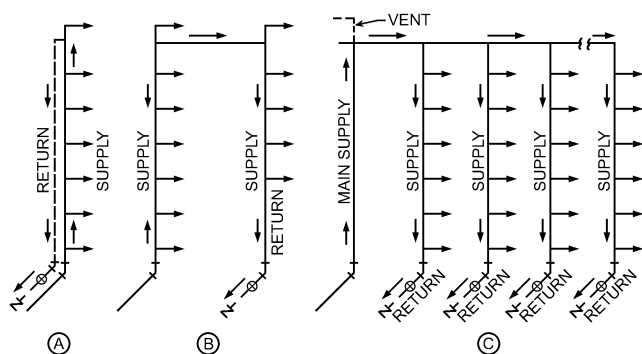
Fig. 2 Arrangements of Hot-Water Circulation Lines

3. Determine pump capacity as follows:

$$Q_p = \frac{q}{60\rho c_p \Delta t} \tag{9}$$

where

Q_p = pump capacity, gpm
q = heat loss, Btu/h
ρ = density of water = 8.25 lb/gal (120°F)
c_p = specific heat of water = 1 Btu/lb·°F
Δt = allowable temperature drop, °F

For a 20°F allowable temperature drop,

$$Q_p(\text{gpm}) = \frac{q}{60 \times 8.25 \times 1 \times 20} = \frac{q}{9900} \tag{10}$$

Caution: This calculation assumes that a 20°F temperature drop is acceptable at the last fixture.

4. Select a pump to provide the required flow rate, and obtain from the pump curves the pressure created at this flow.
5. Multiply the head by 100 and divide by the total length of hot water return piping to determine the allowable friction loss per 100 ft of pipe.
6. Determine the required flow in each circulating loop, and size the hot water return pipe based on this flow and the allowable friction loss from Step 5.

Where multiple risers or horizontal loops are used, balancing valves with means of testing are recommended in the return lines. A swing-type check valve should be placed in each return to prevent entry of cold water or reversal of flow, particularly during periods of high hot-water demand.

Three common methods of arranging circulation lines are shown in Figure 2. Although the diagrams apply to multistory buildings, arrangements (A) and (B) are also used in residential designs. In circulation systems, air venting, pressure drops through the heaters and storage tanks, balancing, and line losses should be considered. In Figures 2A and 2B, air is vented by connecting the circulating line below the top fixture supply. With this arrangement, air is eliminated from the system each time the top fixture is opened. Generally, for small installations, a nominal pipe size (NPS) 1/2 or 3/4 in. hot-water return is ample.

All storage tanks and piping on recirculating systems should be insulated as recommended by the ASHRAE *Standard* 90 series and *Standard* 100.

Heat-Traced, Nonreturn Piping

In this system, the fixtures can be as remote as in the return piping. The hot-water supply piping is heat traced with electric resistance heating cable preinstalled under the pipe insulation. Electrical energy input is self-regulated by the cable's construction to maintain the required water temperature at the fixtures. No return piping system or circulation pump is required.

Multiple Water Heaters

Depending on fixture spacing, required pipe lengths, and draw spacing, it may be more energy-efficient (and sometimes provide lower first cost) to use more than one water heater rather than using extensive piping runs. Energy losses from high-efficiency water heaters can be lower than recirculation-loop piping heat losses if the distance from water heaters to fixtures exceeds 30 to 60 ft (Hiller 2005a). Although there are considerations beyond energy use, such as installation, maintenance, and space requirements, using more than one water heater should always be evaluated when designing water heating systems, even in residences, because of the potentially large energy savings.

Special Piping—Commercial Dishwashers

Adequate flow rate and pressure must be maintained for automatic dishwashers in commercial kitchens. To reduce operating difficulties, piping for automatic dishwashers should be installed according to the following recommendations:

*   The cold-water feed line to the water heater should be no smaller than NPS 1.
*   The supply line that carries 180°F water from the water heater to the dishwasher should not be smaller than NPS 3/4.
*   No auxiliary feed lines should connect to the 180°F supply line.
*   A return line should be installed if the source of 180°F water is more than 5 ft from the dishwasher.
*   Forced circulation by a pump should be used if the water heater is installed on the same level as the dishwasher, if the length of return piping is more than 60 ft, or if the water lines are trapped.
*   If a circulating pump is used, it is generally installed in the return line. It may be controlled by (1) the dishwasher wash switch, (2) a manual switch located near the dishwasher, or (3) an immersion or strap-on thermostat located in the return line.
*   A pressure-reducing valve should be installed in the low-temperature supply line to a booster water heater, but external to a recirculating loop. It should be adjusted, with the water flowing, to the value stated by the washer manufacturer (typically 20 psi).
*   A check valve should be installed in the return circulating line.
*   If a check-valve water meter or a backflow prevention device is installed in the cold-water line ahead of the heater, it is necessary to install a properly sized diaphragm-type expansion tank between the water meter or prevention device and the heater.
*   National Sanitation Foundation (NSF) standards require an NPS 1/4 IPS connection for a pressure gage mounted adjacent to the supply side of the control valve. They also require a water-line strainer ahead of any electrically operated control valve (Figure 3).
*   NSF standards do not allow copper water lines that are not under constant pressure, except for the line downstream of the solenoid valve on the rinse line to the cabinet.

Water Pressure—Commercial Kitchens

Proper flow pressure must be maintained to achieve efficient dishwashing. NSF standards for dishwasher water flow pressure are 15 psig minimum, 25 psig maximum, and 20 psig ideal. Flow pressure is the line pressure measured when water is flowing through the rinse arms of the dishwasher.

Low flow pressure can be caused by undersized water piping, stoppage in piping, or excess pressure drop through heaters. Low water pressure causes an inadequate rinse, resulting in poor drying and sanitizing of the dishes. If flow pressure in the supply line to the dishwasher is below 15 psig, a booster pump or other means should be installed to provide supply water at 20 psig.

Flow pressure over 25 psig causes atomization of the 180°F rinse water, resulting in excessive temperature drop (which can be as much as 15°F between rinse nozzle and dishes). A pressure regulator
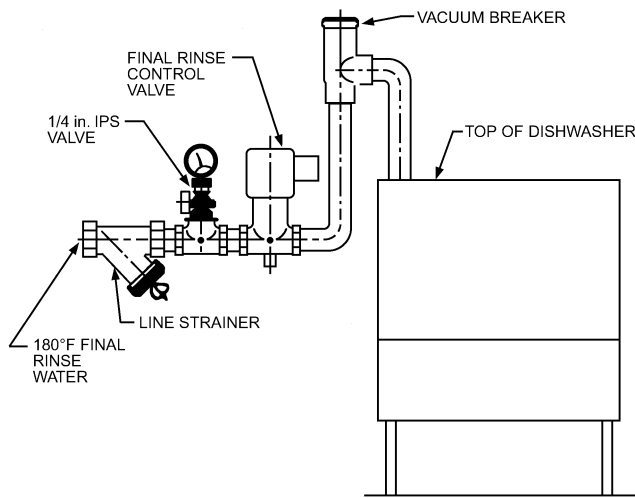
Fig. 3 National Sanitation Foundation (NSF) Plumbing Requirements for Commercial Dishwasher
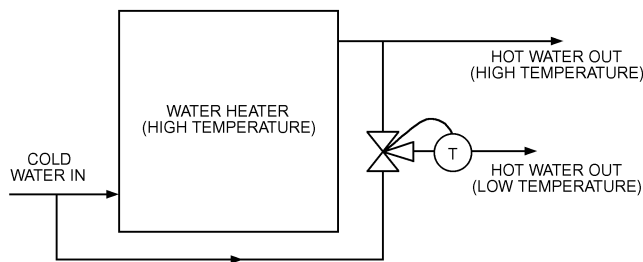
Fig. 4 Two-Temperature Service with Mixing Valve

Fig. 5 Two-Temperature Service with Primary Heater and Booster Heater in Series

Fig. 6 Two-Temperature Service with Separate Heater for Each Service

Fig. 7 Reverse/Return Manifold System

should be installed in the supply water line adjacent to the dishwasher and external to the return circulating loop (if used). The regulator should be set to maintain a pressure of 20 psig.

Two-Temperature Service

Where multiple temperature requirements are met by a single system, the system temperature is determined by the maximum temperature needed. Where the bulk of the hot water is needed at the higher temperature, lower temperatures can be obtained by mixing hot and cold water. Automatic mixing valves reduce the temperature of the hot water available at certain outlets to prevent injury or damage (Figure 4). Applicable codes should be consulted for mixing valve requirements.

Where predominant use is at a lower temperature, the common design heats all water to the lower temperature and then uses a separate booster heater to further heat the water for the higher-temperature service (Figure 5). This method offers better protection against scalding.

A third method uses separate heaters for the higher-temperature service (Figure 6). It is common practice to cross-connect the two heaters, so that one heater can serve the complete installation temporarily while the other is valved off for maintenance. Each heater should be sized for the total load unless hot-water consumption can be reduced during maintenance periods.

Manifolding

Where one heater does not have sufficient capacity, two or more water heaters may be installed in parallel. If blending is needed, a single mixing valve of adequate capacity should be used. It is difficult to obtain even flow through parallel mixing valves.

Heaters installed in parallel should have similar specifications: the same input and storage capacity, with inlet and outlet piping arranged so that an equal flow is received from each heater under all demand conditions.

An easy way to get balanced, parallel flow is to use reverse/return piping (Figure 7). The unit having its inlet closest to the cold-water supply is piped so that its outlet is farthest from the hot-water supply line. Quite often this results in a hot-water supply line that reverses direction (see dashed line, Figure 7) to bring it back to the first unit in line; hence the name reverse/return.

TERMINAL HOT-WATER USAGE DEVICES

Details on the vast number of devices using service hot water are beyond the scope of this chapter. Nonetheless, they are important to a successful overall design. Consult the manufacturer's literature for information on required flow rates, temperature limits, and/or other operating factors for specific items.

WATER QUALITY, SCALE, AND CORROSION

A complete water analysis and an understanding of system requirements are needed to protect water-heating systems from scale and corrosion. Analysis shows whether water is hard or soft.
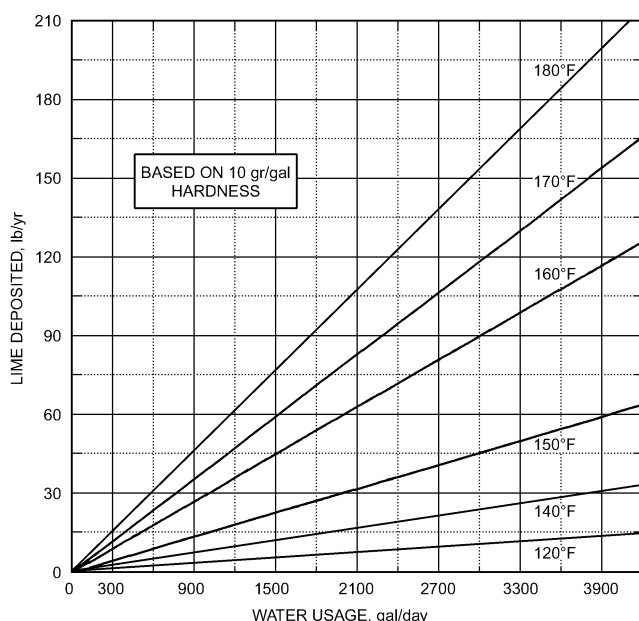
Fig. 8   Lime Deposited Versus Temperature and Water Use
(Based on data from Purdue University Bulletin No. 74)

Hard water, unless treated, causes scaling or liming of heat transfer and water storage surfaces; soft water may aggravate corrosion problems and anode consumption (Talbert et al. 1986).

Scale formation is also affected by system requirements and equipment. As shown in Figure 8, the rate of scaling increases with temperature and use because calcium carbonate and other scaling compounds lose solubility at higher temperatures. In water tube-type equipment, scaling problems can be offset by increasing water velocity over the heat transfer surfaces, which reduces the tube surface temperature. Also, flow turbulence, if high enough, works to keep any scale that does precipitate off the surface. When water hardness is over 8 gr/gal, water softening or other water treatment is often recommended.

Corrosion problems increase with temperature because corrosive oxygen and carbon dioxide gases are released from the water. Electrical conductivity also increases with temperature, enhancing electrochemical reactions such as rusting (Taborek et al. 1972). A deposit of scale provides some protection from corrosion; however, this deposit also reduces the heat transfer rate, and it is not under the control of the system designer (Talbert et al. 1986).

Steel vessels can be protected to varying degrees by galvanizing or by lining with copper, glass, cement, electroless nickel-phosphorus, or other corrosion-resistant material. Glass-lined vessels are almost always supplied with electrochemical protection. Typically, one or more anode rods of magnesium, aluminum, or zinc alloy are installed in the vessel by the manufacturer. This electrochemically active material sacrifices itself to reduce or prevent corrosion of the tank (the cathode). Higher temperature, softened water, and high water use may lead to rapid anode consumption. Manufacturers recommend periodic replacement of the anode rod(s) to prolong the life of the vessel. Some waters have very little electrochemical activity. In this instance, a standard anode shows little or no activity, and the vessel is not adequately protected. If this condition is suspected, consult the equipment manufacturer on the possible need for a high-potential anode, or consider using vessels made of nonferrous material.

Water heaters and hot-water storage tanks constructed of stainless steel, copper, or other nonferrous alloys are protected against oxygen corrosion. However, care must still be taken, as some stainless steel may be adversely affected by chlorides, and copper may be attacked by ammonia or carbon dioxide.

SAFETY DEVICES FOR HOT-WATER SUPPLIES

Regulatory agencies differ as to the selection of protective devices and methods of installation. It is therefore essential to check and comply with the manufacturer's instructions and the applicable local codes. In the absence of such instructions and codes, the following recommendations may be used as a guide:

- Water expands when it is heated. Although the water-heating system is initially under service pressure, the pressure rises rapidly if backflow is prevented by devices such as a check valve, pressure-reducing valve, or backflow preventer in the cold-water line or by temporarily shutting off the cold-water valve. When backflow is prevented, the pressure rise during heating may cause the safety relief valve to weep to relieve the pressure. However, if the safety relief valve is inadequate, inoperative, or missing, pressure rise may rupture the tank or cause other damage. Systems having this potential problem must be protected by a properly sized expansion tank located on the cold-water line downstream of and as close as practical to the device preventing backflow.
- Temperature-limiting devices (energy cutoff/high limit) prevent water temperatures from exceeding 210°F by stopping the flow of fuel or energy. These devices should be listed and labeled by a recognized certifying agency.
- Safety relief valves open when pressure exceeds the valve setting. These valves are typically applied to water heating and hot-water supply boilers. The set pressure should not exceed the maximum allowable working pressure of the boiler. The heat input pressure steam rating (in Btu/h) should equal or exceed the maximum output rating for the boiler. The valves should comply with current applicable standards or the ASME *Boiler and Pressure Vessel Code*.
- Temperature and pressure safety relief valves also open if the water temperature reaches 210°F. These valves are typically applied to water heaters and hot-water storage tanks. The heat input temperature/steam rating (in Btu/h) should equal or exceed the heat input rating of the water heater. Combination temperature- and pressure-relief valves should be installed with the temperature-sensitive element located in the top 6 in. of the tank (i.e., where the water is hottest).
- To reduce scald hazards, discharge temperature at fixtures accessible to the occupant should not exceed 120°F. Thermostatically controlled mixing valves can be used to blend hot and cold water to maintain safe service hot-water temperatures.
- A relief valve should be installed in any part of the system containing a heat input device that can be isolated by valves. The heat input device may be solar water-heating panels, desuperheater water heaters, heat recovery devices, or similar equipment.

SPECIAL CONCERNS

Legionella pneumophila (Legionnaires' Disease)

Legionnaires' disease (a form of severe pneumonia) is caused by inhaling the bacteria *Legionella pneumophila*. It has been discovered in the service water systems of various buildings throughout the world. Infection has often been traced to *L. pneumophila* colonies in shower heads. Ciesielski et al. (1984) determined that *L. pneumophila* can colonize in hot water maintained at 115°F or lower. Segments of service water systems in which water stagnates (e.g., shower heads, faucet aerators, unused or infrequently used piping branches, some sections of storage water heaters) provide ideal breeding locations.

Service water temperature in the 140°F range is recommended to limit the potential for *L. pneumophila* growth. This high temperature increases the potential for scalding, so care must be taken such as installing an anti-scald or mixing valve. Supervised periodic flushing of fixture heads with 170°F water is recommended in hospitals and health care facilities because the already weakened pa-
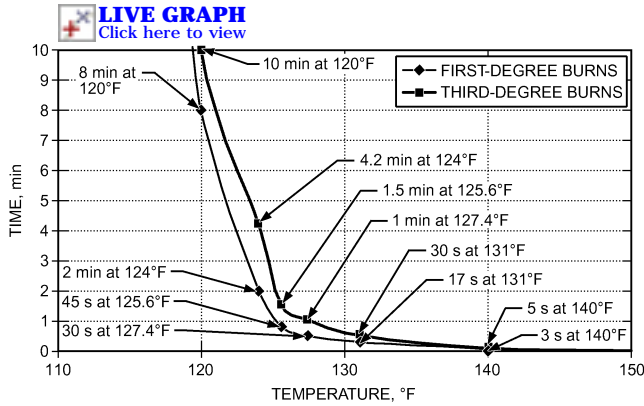
Fig. 9   Time for Adult Skin Burns in Hot Water

tients are generally more susceptible to infection. Although higher temperatures are required for eradication of *Legionella*, lower temperatures may be adequate for prevention. Note, too, that *Legionella* colonies can grow on the cold-water side of the system in stagnant flow areas, especially if those areas can rise in temperature because of heat input from the surroundings.

Note that susceptibility to Legionnaire's disease varies among individuals. People with compromised immune systems (organ transplant patients or otherwise on immunosuppressant drugs, AIDS patients, smokers, elderly, other chronic health conditions or injuries) are at greater risk of contracting the disease at lower exposure levels.

More information on this subject can be found in ASHRAE *Guideline* 12-2000.

Scalding

Scalding is an important concern in design and operation of potable hot-water systems. Figure 9 (Moritz 1947) shows plots of exposure time versus water temperature that results in both first-degree (pain, redness, swelling, minor tissue damage) and full-thickness third-degree (permanent damage, scarring) skin burns in adults. Children burn even more rapidly. Note that, at the high temperatures required to eradicate *Legionella* bacteria (140°F and above), burns can occur almost instantaneously (3 s or less exposure). Safety dictates some tradeoffs to limit scalding injuries (e.g., during pressure transients that may inhibit proper operation of temperature regulating valves) while minimizing risk of Legionnaire's disease.

Temperature Requirement

Typical temperature requirements for some services are shown in Table 3. A 140°F water temperature minimizes flue gas condensation in the equipment.

Hot Water from Tanks and Storage Systems

With storage systems, 60 to 80% of the hot water in a tank is assumed to be usable before dilution by cold water lowers the temperature below an acceptable level. However, better designs can exceed 90%. Thus, the maximum hot water available from a self-contained storage heater is usually

$$V_t = Rd + MS_t \qquad (11)$$

where

V_t = available hot water, gal
R = recovery rate at required temperature, gph
d = duration of peak hot-water demand, h
M = ratio of usable water to storage tank capacity
S_t = storage capacity of heater tank, gal

However, Equation (11) only applies if the water draw rate is less than the available reheat rate. Otherwise, the tank cannot heat the

Table 3   Representative Hot-Water Temperatures

Use	Temperature, °F
Lavatory	
Hand washing	105
Shaving	115
Showers and tubs	110
Therapeutic baths	95
Commercial or institutional laundry, based on fabric	up to 180
Residential dish washing and laundry	140
Surgical scrubbing	110
Commercial spray-type dish washing[a]	
Single- or multiple-tank hood or rack type	
Wash	150 min.
Final rinse	180 to 195
Single-tank conveyor type	
Wash	160 min.
Final rinse	180 to 195
Single-tank rack or door type	
Single-temperature wash and rinse	165 min.
Chemical sanitizing types[b]	140
Multiple-tank conveyor type	
Wash	150 min.
Pumped rinse	160 min.
Final rinse	180 to 195
Chemical sanitizing glass washer	
Wash	140
Rinse	75 min.

[a]As required by NSF.
[b]See manufacturer for actual temperature required.

flowing water to a usable temperature during the draw, and V_t drops to the same as an unfired tank. For example, a fossil-fuel-fired heater with a fuel input rate of 44,000 Btu/h and an input efficiency of 80% can raise the temperature of water being drawn through a storage tank at a rate of 3 gpm by approximately 23°F. If the entering cold-water temperature is 60°F, the water will be heated to only 83°F, too cold to be useful, so the heating rate cannot contribute to effective storage tank capacity under a prolonged draw at this flow rate. In reality, draw rates are rarely constant during peak draw or other times. Computer simulation models allow equipment sizing under these more realistic conditions (Hiller 1992).

Maximum usable hot water from an unfired tank is

$$V_a = MS_a \qquad (12)$$

where

V_a = usable water available from unfired tank, gal
S_a = capacity of unfired tank, gal

Note: Assumes tank water at required temperature.

Hot water obtained from a water heater using a storage heater with an auxiliary storage tank is

$$V_z = V_t + V_a \qquad (13)$$

where V_z = total hot water available during one peak, in gallons.

Placement of Water Heaters

Many types of water heaters may be expected to leak at the end of their useful life. They should be placed where leakage will not cause damage. Alternatively, suitable drain pans piped to drains must be provided.

Water heaters not requiring combustion air may generally be placed in any suitable location, as long as relief valve discharge pipes open to a safe location.

Water heaters requiring ambient combustion air must be located in areas with air openings large enough to admit the required combustion/dilution air (see NFPA *Standard* 54/ANSI Z223.1).

For water heaters located in areas where flammable vapors are likely to be present, precautions should be taken against ignition. For water heaters installed in residential garages, additional precautions should be taken. Consult local codes for additional requirements or see sections 5.1.9 through 5.1.12 of NFPA *Standard* 54/ANSI Z223.1.

Outside models with a weather-proofed jacket are available. Direct-vent gas- and oil-fired models are also available; they are to be installed inside, but are not vented through a conventional chimney or gas vent. They use ambient air for combustion. They must be installed with the means specified by the manufacturer for venting (typically horizontal) and for supplying air for combustion from outside the building.

HOT-WATER REQUIREMENTS AND STORAGE EQUIPMENT SIZING

Methods for sizing storage water heaters vary. Those using recovery versus storage curves are based on extensive research. All methods provide adequate hot water if the designer allows for unusual conditions. To serve a hot-water load adequately, the needs of both the peak energy withdrawal rate and total integrated energy delivery for end uses must be met. Meeting these needs can be done either by providing a heating rate large enough to meet the peak energy withdrawal rate of the system (and modulating that heating input for smaller loads), or by providing a lower heating rate combined with storage (from which the peak rates can be satisfied). Lower costs are usually achieved by using at least some storage. A variety of different heating rate/storage volume combinations can be used to meet the needs of a given water-heating load profile (Hiller 1998).

Load Diversity

The greatest difficulty in designing water-heating systems comes from uncertainty about design hot-water loads, especially for buildings not yet built. Although it is fairly simple to test maximum flow rates of various hot-water fixtures and appliances, actual flow rates and durations are user-dependent. Moreover, the timing of different hot-water use events varies from day to day, with some overlap, but almost never will all fixtures be used simultaneously. As the number of hot-water-using fixtures and appliances grows, the percent of those fixtures used simultaneously decreases.

Some of the hot-water load information in this chapter is based on limited-scale field testing combined with statistical analysis to estimate load demand or **diversity** factors (percent of total possible load that is ever actually used at one time) versus number of end use points, number of people, etc. Much of the work to provide these diversity factors dates from the 1930s to the 1960s; it remains, however, the best information currently available (with a few exceptions, as noted). Of greatest concern is the fact that most of the data from those early studies were for fixtures that used water at much higher flow rates than modern energy-efficient fixtures (e.g., low-flow shower heads and sink aerators, energy-efficient washing machines and dishwashers). Some recent research has provided limited information on hot-water use by more modern fixtures, and on their use diversity (Becker et al. 1991; Goldner 1994a, 1994b; Goldner and Price 1999; Hiller 1998; Hiller and Lowenstein 1996, 1998; Thrasher and DeWerth 1994), but much more information in a variety of applications is needed before the design procedures can be updated. Using the older load diversity information usually results in a water-heating system that adequately serves the loads, but often results in substantial oversizing. Oversizing can be a deterrent to using modern high-efficiency water-heating equipment, which may

Table 4 Typical Residential Use of Hot Water

Use	High Flow, Gallons/Task	Low Flow (Water Savers Used), Gallons/Task	Ultralow Flow, Gallons/Task
Food preparation	5	3	3
Hand dish washing	4	4	3
Automatic dishwasher	15	15	3 to 10
Clothes washer	32	21	5 to 15
Shower or bath	20	15	10 to 15
Face and hand washing	4	2	1 to 2

have higher first cost per unit of capacity than less efficient equipment. Sustainable design must consider these effects.

Residential

Table 4 shows typical hot-water usage in a residence, including usage rates of modern ultralow-use appliances and fixtures. It is more difficult to show typical values for newer devices, because some automatically adjust the amount of hot water they use based on sensed load or cycle setting. In its *Minimum Property Standards for Housing*, the U.S. Department of Housing and Urban Development (HUD 1994) established minimum permissible water heater sizes (Table 5). Storage water heaters may vary from the sizes shown if combinations of recovery and storage are used that produce the required 1 h draw.

The first-hour rating (FHR) is the theoretical maximum amount of hot water that the water heater can supply in 1 h of operation under specific test conditions (DOE 1998). The linear regression lines shown in Figure 10 represent the FHR for 1556 electric heaters and 2901 gas heaters [GAMA (Continuous Maintenance); Hiller 1998]. Regression lines are not included for oil-fired and heat-pump water heaters because of limited data. The FHR represents water-heater performance characteristics that are similar to those represented by the 1 h draw values listed in Table 5. Residential water-heating equipment sizing is frequently driven by amounts of water used over periods of considerably less than 1 h, often as short as 15 minutes. (Hiller 1998) Over these short periods, storage tank volume is a better indicator of hot-water delivery capability than first-hour rating for residential applications.

Another factor to consider when sizing water heaters is the set-point temperature. At lower storage tank water temperatures, the tank volume and/or energy input rate may need to be increased to meet a given hot-water demand. Currently, manufacturers ship residential water heaters with a recommendation that the initial set point be approximately 120°F to minimize the potential for scalding. Reduced set points generally lower standby losses and increase the water heater's efficiency and recovery capacity, but may also reduce the amount of hot water available.

The structure and lifestyle of a typical family (variations in family size, age of family members, presence and age of children, hot-water use volume and temperature, and other factors) cause hot-water consumption demand patterns to fluctuate widely in both magnitude and time distribution.

Perlman and Mills (1985) developed the overall and peak average hot-water use volumes shown in Table 6. Average hourly patterns and 95% confidence level profiles are illustrated in Figures 11 and 12. Samples of results from the analysis of similarities in hot-water use are given in Figures 13 and 14.

Commercial and Institutional

Most commercial and institutional establishments use hot or warm water. The specific requirements vary in total volume, flow rate, duration of peak load period, and temperature. Water heaters and systems should be selected based on these requirements.

This section covers sizing recommendations for central storage water-heating systems. Hot-water usage data and sizing curves for dormitories, motels, nursing homes, office buildings, food service

LIVE GRAPH
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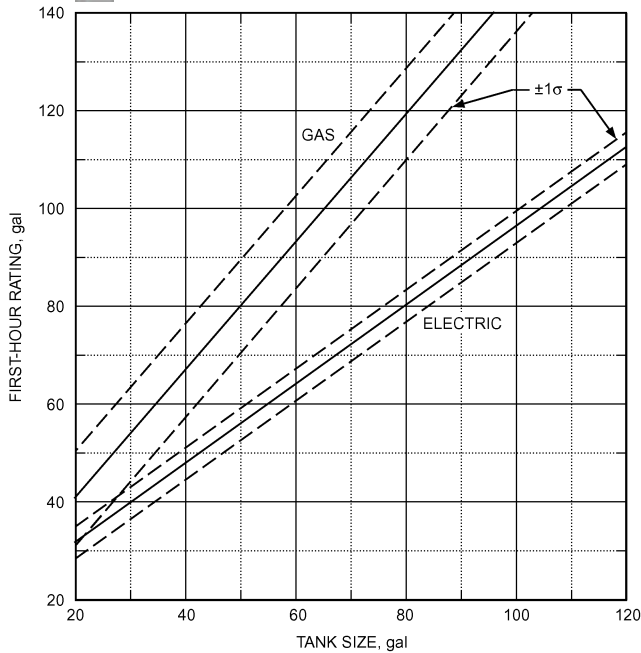
Fig. 10 First-Hour Rating (FHR) Relationships for Residential Water Heaters

Fig. 11 Residential Average Hourly Hot-Water Use

Fig. 12 Residential Hourly Hot-Water Use, 95% Confidence Level
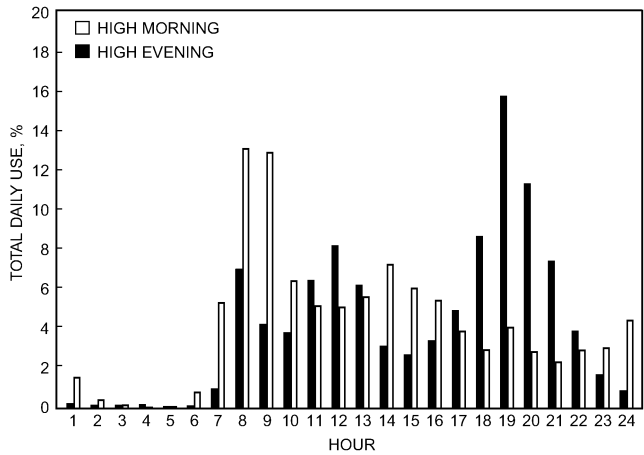
Fig. 13 Residential Hourly Hot-Water Use Pattern for Selected High Morning and High Evening Users

establishments, apartments, and schools are based on EEI-sponsored research (Werden and Spielvogel 1969a, 1969b). Caution must be taken in applying these data to small buildings. Also, within any given category there may be significant variation. For example, the motel category encompasses standard, luxury, resort, and convention motels.

When additional hot-water requirements exist, increase the recovery and/or storage capacity accordingly. For example, if there is food service in an office building, the recovery and storage capacities required for each additional hot-water use should be added when sizing a single central water-heating system.

Peak hourly and daily demands for various categories of commercial and institutional buildings are shown in Table 7. These demands for central-storage hot water represent the maximum flows metered in this 129-building study, excluding extremely high and very infrequent peaks. Table 7 also shows average hot-water consumption figures for these buildings. Averages for schools and food service establishments are based on actual days of operation;

all others are based on total days. These averages can be used to estimate monthly consumption of hot water.

Research conducted for ASHRAE (Becker et al. 1991; Thrasher and DeWerth 1994) and others (Goldner 1994a, 1994b) included a compilation and review of service hot-water use information in commercial and multifamily structures along with new monitoring data. Some of this work found consumption comparable to those shown in Table 7; however, many of the studies showed higher consumption.

Dormitories. Hot-water requirements for college dormitories generally include showers, lavatories, service sinks, and clothes washers. Peak demand usually results from the use of showers. Load profiles and hourly consumption data indicate that peaks may last 1 or 2 h and then taper off substantially. Peaks occur predominantly in the evening, mainly around midnight. The figures do not include hot water used for food service.

Military Barracks. Design criteria for military barracks are available from the engineering departments of the U.S. Department of Defense. Some measured data exist for hot-water use in these facilities. For published data, contact the U.S. Army Corps of Engineers or Naval Facilities Engineering Command.

Motels. Domestic hot-water requirements are for tubs and showers, lavatories, and general cleaning purposes. Recommendations are based on tests at low- and high-rise motels located in urban, suburban, rural, highway, and resort areas. Peak demand, usually from

Table 5   HUD-FHA Minimum Water Heater Capacities for One- and Two-Family Living Units

Number of Baths	1 to 1.5			2 to 2.5				3 to 3.5			
Number of Bedrooms	1	2	3	2	3	4	5	3	4	5	6
Gas[a]											
Storage, gal	20	30	30	30	40	40	50	40	50	50	50
1000 Btu/h input	27	36	36	36	36	38	47	38	38	47	50
1 h draw, gal	43	60	60	60	70	72	90	72	82	90	92
Recovery, gph	23	30	30	30	30	32	40	32	32	40	42
Electric[a]											
Storage, gal	20	30	40	40	50	50	66	50	66	66	80
kW input	2.5	3.5	4.5	4.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
1 h draw, gal	30	44	58	58	72	72	88	72	88	88	102
Recovery, gph	10	14	18	18	22	22	22	22	22	22	22
Oil[a]											
Storage, gal	30	30	30	30	30	30	30	30	30	30	30
1000 Btu/h input	70	70	70	70	70	70	70	70	70	70	70
1 h draw, gal	89	89	89	89	89	89	89	89	89	89	89
Recovery, gph	59	59	59	59	59	59	59	59	59	59	59
Tank-type indirect[b,c]											
I-W-H-rated draw, gal in 3 h, 100°F rise		40	40	66	66[e]	66		66	66	66	66
Manufacturer-rated draw, gal in 3 h, 100°F rise		49	49	75	75[e]	75		75	75	75	75
Tank capacity, gal		66	66	66	66[e]	82		66	82	82	82
Tankless-type indirect[c,d]											
I-W-H-rated draw, gpm, 100°F rise		2.75	2.75		3.25	3.25[e]	3.75	3.25	3.75	3.75	3.75
Manufacturer-rated draw, gal in 5 min, 100°F rise		15	15		25	25[e]	35	25	35	35	35

[a]Storage capacity, input, and recovery requirements indicated are typical and may vary with manufacturer. Any combination of requirements to produce stated 1 h draw is satisfactory.

[b]Boiler-connected water heater capacities (180°F boiler water, internal or external connection).

[c]Heater capacities and inputs are minimum allowable. Variations in tank size are permitted when recovery is based on 4 gph/kW at 100°F rise for electrical, AGA recovery ratings for gas, and IBR ratings for steam and hot-water heaters.

[d]Boiler-connected heater capacities (200°F boiler water, internal or external connection).

[e]Also for 1 to 1.5 baths and 4 bedrooms for indirect water heaters.
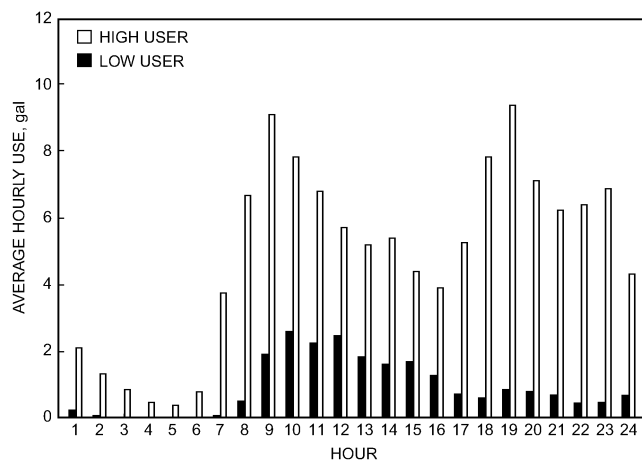
Fig. 14   Residential Average Hourly Hot-Water Use Patterns for Low and High Users

Table 6   Overall (OVL) and Peak Average Hot-Water Use

	Average Hot-Water Use, gal							
	Hourly		Daily		Weekly		Monthly	
Group	OVL	Peak	OVL	Peak	OVL	Peak	OVL	Peak
All families	2.6	4.6	62.4	67.1	436	495	1897	2034
"Typical" families	2.6	5.8	63.1	66.6	442	528	1921	2078

shower use, may last 1 or 2 h and then drop off sharply. Food service, laundry, and swimming pool requirements are not included.

Nursing Homes. Hot water is required for tubs and showers, wash basins, service sinks, kitchen equipment, and general cleaning. These figures include hot water for kitchen use. When other equipment, such as that for heavy laundry and hydrotherapy purposes, is to be used, its hot-water requirement should be added.

Office Buildings. Hot-water requirements are primarily for cleaning and lavatory use by occupants and visitors. Hot-water use for food service within office buildings is not included.

Food Service Establishments. Hot-water requirements are primarily for dish washing. Other uses include food preparation, cleaning pots and pans and floors, and hand washing for employees and customers. Recommendations are for establishments serving food at tables, counters, booths, and parked cars. Establishments that use disposable service exclusively are not covered in Table 7.

Dish washing, as metered in these tests, is based on normal practice of dish washing after meals, not on indiscriminate or continuous use of machines irrespective of the flow of soiled dishes. Recommendations include hot water supplied to dishwasher booster heaters.

Apartments. Hot-water requirements for both garden-type and high-rise apartments are for one- and two-bath apartments, for showers, lavatories, kitchen sinks, dishwashers, clothes washers, and general cleaning purposes. Clothes washers can be either in individual apartments or centrally located. These data apply to central water-heating systems only.

Elementary Schools. Hot-water requirements are for lavatories, cafeteria and kitchen use, and general cleaning purposes. When showers are used, their additional hot-water requirements should be added. Recommendations include hot water for dishwashers but not for extended school operation such as evening classes.

High Schools. Senior high schools, grades 9 or 10 through 12, require hot water for showers, lavatories, dishwashers, kitchens, and general cleaning. Junior high schools, grades 7 through 8 or 9, have requirements similar to those of the senior high schools. Junior high schools without showers follow the recommendations for elementary schools.

Requirements for high schools are based on daytime use. Recommendations do not take into account hot-water use for additional activities such as night school. In such cases, the maximum hourly demand remains the same, but the maximum and average daily use increase, usually by the number of additional people using showers and, to a lesser extent, eating and washing facilities.

Table 7 Hot-Water Demands and Use for Various Types of Buildings*

Type of Building	Maximum Hourly	Maximum Daily	Average Daily
Men's dormitories	3.8 gal/student	22.0 gal/student	13.1 gal/student
Women's dormitories	5.0 gal/student	26.5 gal/student	12.3 gal/student
Motels: Number of units[a]			
20 or less	6.0 gal/unit	35.0 gal/unit	20.0 gal/unit
60	5.0 gal/unit	25.0 gal/unit	14.0 gal/unit
100 or more	4.0 gal/unit	15.0 gal/unit	10.0 gal/unit
Nursing homes	4.5 gal/bed	30.0 gal/bed	18.4 gal/bed
Office buildings	0.4 gal/person	2.0 gal/person	1.0 gal/person
Food service establishments			
Type A: Full-meal restaurants and cafeterias	1.5 gal/max meals/h	11.0 gal/max meals/day	2.4 gal/average meals/day[b]
Type B: Drive-ins, grills, luncheonettes, sandwich, and snack shops	0.7 gal/max meals/h	6.0 gal/max meals/day	0.7 gal/average meals/day[b]
Apartment houses: Number of apartments			
20 or less	12.0 gal/apartment	80.0 gal/apartment	42.0 gal/apartment
50	10.0 gal/apartment	73.0 gal/apartment	40.0 gal/apartment
75	8.5 gal/apartment	66.0 gal/apartment	38.0 gal/apartment
100	7.0 gal/apartment	60.0 gal/apartment	37.0 gal/apartment
200 or more	5.0 gal/apartment	50.0 gal/apartment	35.0 gal/apartment
Elementary schools	0.6 gal/student	1.5 gal/student	0.6 gal/student[b]
Junior and senior high schools	1.0 gal/student	3.6 gal/student	1.8 gal/student[b]

*Data predate modern low-flow fixtures and appliances.   [a]Interpolate for intermediate values.   [b]Per day of operation.

Additional Data.

Fast Food Restaurants. Hot water is used for food preparation, cleanup, and rest rooms. Dish washing is usually not a significant load. In most facilities, peak usage occurs during the cleanup period, typically soon after opening and immediately before closing. Hot-water consumption varies significantly among individual facilities. Fast food restaurants typically consume 250 to 500 gal per day (EPRI 1994).

Supermarkets. The trend in supermarket design is to incorporate food preparation and food service functions, substantially increasing the usage of hot water. Peak usage is usually associated with cleanup periods, often at night, with a total consumption of 300 to 1000 gal per day (EPRI 1994).

Apartments. Table 8 shows cumulative hot-water use over time for apartment buildings, taken from a series of field tests by Becker et al. (1991), Goldner (1994a, 1994b), Goldner and Price (1999), and Thrasher and DeWerth (1994). These data include use diversity information, and enable use of modern water-heating equipment sizing methods for this building type, making it easy to understand the variety of heating rate and storage volume combinations that can serve a given load profile (see Example 1). Unlike Table 7, Table 8 presents low/medium/high (LMH) guidelines rather than specific singular volumes, and gives better time resolution of peak hot-water use information. The same information is shown graphically in Figure 15.

The low-use peak hot-water consumption profile represents the lowest peak profile seen in the tests, and is generally associated with apartment buildings having mostly a mix of the following occupant demographics:

- All occupants working
- One person working, while one stays at home
- Seniors
- Couples
- Middle income
- Higher population density

The medium-use peak hot-water consumption profile represents the overall average highest peak profile seen in the tests, and is generally associated with apartment buildings having mostly a mix of the following occupant demographics:

- Families
- Singles

Table 8 Hot-Water Demand and Use Guidelines for Apartment Buildings
(Gallons per Person at 120°F Delivered to Fixtures)

Guideline	Peak Minutes						Maximum Daily	Average Daily
	5	15	30	60	120	180		
Low	0.4	1.0	1.7	2.8	4.5	6.1	20	14
Medium	0.7	1.7	2.9	4.8	8.0	11.0	49	30
High	1.2	3.0	5.1	8.5	14.5	19.0	90	54
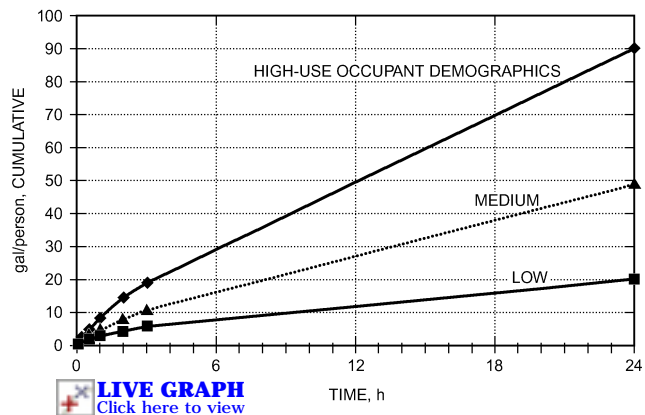
Fig. 15 Apartment Building Cumulative Hot-Water Use Versus Time (from Table 8)

- On public assistance
- Single-parent households

The high-use peak hot-water consumption profile represents the highest peak profile seen in the tests, and is generally associated with apartment buildings having mostly a mix of the following occupant demographics:

- High percentage of children
- Low income
- On public assistance
- No occupants working
- Families

• Single-parent households

In applying these guidelines, the designer should note that a building may outlast its current use. This may be a reason to increase the design capacity for domestic hot water or allow space and connections for future enhancement of the service hot-water system. Building management practices, such as the explicit prohibition (in the lease) of apartment clothes washers or the existence of bath/kitchen hook-ups, should be factored into the design process. A diversity factor that lowers the probability of coincident consumption should also be used in larger buildings.

The information in Table 8 and Figure 15 generates a water-heating equipment sizing method for apartment buildings. The cumulative total hot-water consumption versus time (which includes all necessary load diversity information) can be used to select a range of heating rate and storage volume options, all of which will satisfy the load. The key is that plots of cumulative total hot-water consumption versus time as shown in Figure 15 also represent, by the slope of a line drawn from zero time through the cumulative volume used at any give time, the average hot-water flow rate up to that point in time. Up to any point in time, the minimum average heating rate needed to satisfy the load is one that can heat the average hot-water flow rate through that time from the local entering cold-water temperature to the water-heating system delivery temperature. The storage volume needed for that heating rate is the total cumulative flow through that time (Hiller 1998). To evaluate the range of minimum required heating rates and their corresponding minimum required storage tank volumes, it is easiest to pick various volumes in Figure 15 or Table 8, then determine the heating rate and time period that correspond to them, as shown in Example 1. Final selection of water-heating system heating rate and storage size is then made by examining the first and operating costs of the various combinations.

Sizing Examples

Example 1. Evaluate the range of water-heating system heating-rate and storage volume combinations that can serve a 58-unit apartment building occupied by a mix of families, singles, and middle-income couples in which most adults work. The peak expected number of building occupants is 198, based on the assortment of apartment sizes in the building. Assume a water-heating system delivery temperature of 120°F, design entering cold-water temperature of 40°F, and heating device thermal efficiency of 80%.

Solution: The stated occupant demographics represent a medium load. Multiplying the volume per person versus time from the medium values in Table 8 by the number of occupants gives the cumulative amount needed at any point in time and the average flow rate (and hence heating rate) required through that time.

At 5 min, the peak design cumulative volume is (0.7 gal/person) × (198 people) = 138.6 gal. The average flow rate over 5 min is 138.6 gal/ 5 min = 27.72 gal/min. The required heating rate is thus, from Equation (1) and dividing by the input efficiency,

$$q = (27.72 \text{ gal/min})(60 \text{ min/h})(8.4 \text{ lb}_m/\text{gal})(1 \text{ Btu/lb}_m \cdot °F)$$
$$\times (120 - 40°F)/0.8 = 1,397,088 \text{ Btu/h}$$

Assuming 70% of the storage tank volume can be extracted at a useful temperature (the other 30% being degraded by mixing in the tank), the required tank volume for this heating rate is

$$V = 138.6 \text{ gal}/0.7 = 198 \text{ gal}$$

Note that, because the storage capacity exceeds 4000 Btu/h·gal, this system is considered an instantaneous water heater.

At 60 min, (4.8 gal/person)(198 people) = 950.4 gal. Average flow rate = 950.4 gal/60 min = 15.8 gal/min.

$$q = (15.8 \text{ gal/min})(60 \text{ min/h})(8.4 \text{ lb}_m/\text{gal})(1 \text{Btu/lb}_m \cdot °F)$$
$$\times (120 - 40°F)/0.8 = 798,336 \text{ Btu/h}$$

$$V = 950.4 \text{ gal}/0.7 = 1358 \text{ gal}$$

Table 9 Example 1 Heating Rate and Storage Volume Options

Time, min	Gallons per Person	Total Gallons for 198 People	Average Gallons per Minute	Heating Rate, Btu/h	Storage Volume, gal
5	0.7	139	28	1,397,088	198
15	1.7	337	22	1,130,976	481
30	2.9	574	19	964,656	820
60	4.8	950	16	798,336	1358
120	8	1584	13	665,280	2263
180	11	2178	12	609,840	3111
1440	49	9702	7	339,570	13,860

Doing these calculations at other volumes and times yields the combinations of heating rate and storage volume that can serve the load (Table 9).

There are several techniques to size water-heating systems using the more limited draw profile information in older data. Figures 16 to 23 show relationships between recovery and storage capacity for various building categories. Any combination of storage and recovery rates that falls on the proper curve satisfies building requirements. Using the minimum recovery rate and maximum storage capacity on the curves yields the smallest hot-water capacity able to satisfy the building requirement. The higher the recovery rate, the greater the 24 h heating capacity and the smaller the storage capacity required. Note that the data in Figures 16 to 23 predate modern low-flow fixtures and appliances.

These curves can be used to select recovery and storage requirements to accommodate water heaters that have fixed storage or recovery rates. Where hot-water demands are not coincident with peak electric, steam, or gas demands, greater heater inputs can be selected if they do not create additional energy system demands, and the corresponding storage tank size can be selected from the curves.

Ratings of gas-fired water-heating equipment are based on sea-level operation and apply up to 2000 ft. For operation above 2000 ft, and in the absence of specific recommendations from the local authority, equipment ratings should be reduced by 4% for each 1000 ft above sea level before selecting appropriately sized equipment.

Recovery rates in Figures 16 to 23 represent the actual hot water required without considering system heat losses. Heat losses from storage tanks and recirculating hot-water piping should be calculated and added to the recovery rates shown. Storage tanks and hot-water piping must be insulated.

The storage capacities shown are net usable requirements. Assuming that 60 to 80% of the hot water in a storage tank is usable, the actual storage tank size should be increased by 25 to 66% to compensate for unusable hot water.

Figure 24 shows hourly flow profiles for a sample building in each category, so that readers may better understand the nature of energy withdrawal rate profiles that may need to be met in such applications. These buildings were selected from actual metered tests, but are not necessarily typical of all buildings in that category. Figure 24 should not be used for sizing water heaters, because a design load profile for a real building may vary substantially from these limited test cases.

Example 2. Determine the required water heater size for a 300-student women's dormitory for the following criteria:

  a. Storage with minimum recovery rate
  b. Storage with recovery rate of 2.5 gph per student
  c. With the additional requirement for a cafeteria to serve a maximum of 300 meals per hour for minimum recovery rate, combined with item *a*; and for a recovery rate of 1.0 gph per maximum meals per hour, combined with item *b*

Solution:
  a. The minimum recovery rate from Figure 16 for women's dormitories is 1.1 gph per student, or 330 gph total. At this rate, storage
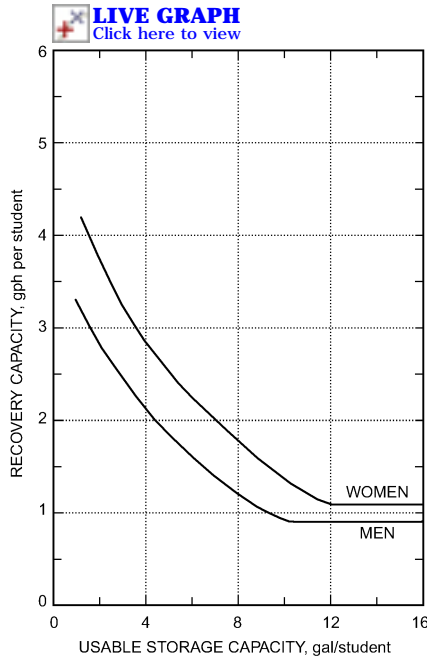
Fig. 16 Dormitories
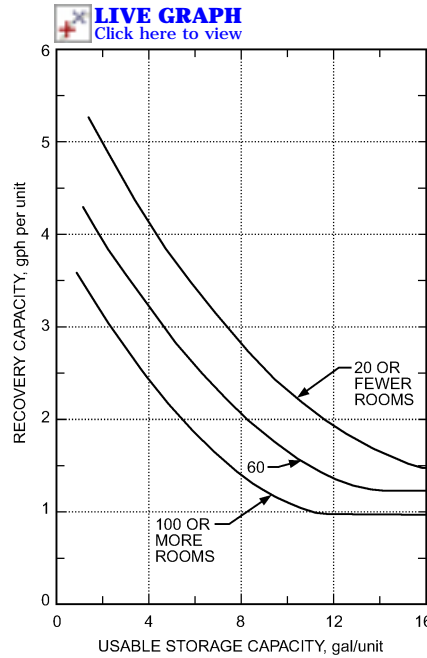
Fig. 17 Motels
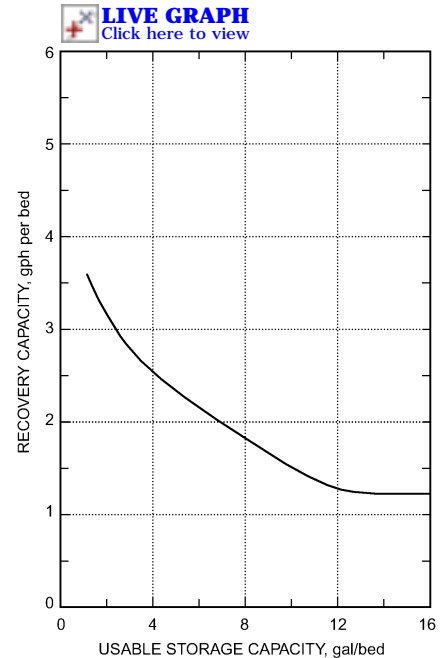
Fig. 18 Nursing Homes

required is 12 gal per student or 3600 gal total. On a 70% net usable basis, the necessary tank size is 3600/0.7 = 5150 gal.

b. The same curve shows 5 gal storage per student at 2.5 gph recovery, or 300 × 5 = 1500 gal storage with recovery of 300 × 2.5 = 750 gph. The tank size is 1500/0.7 = 2150 gal.

c. Requirements for a cafeteria can be determined from Figure 20 and added to those for the dormitory. For the case of minimum recovery rate, the cafeteria (Type A) requires 300 × 0.45 = 135 gph recovery rate and 300 × 7/0.7 = 3000 gal of additional storage. The entire building then requires 330 + 135 = 465 gph recovery and 5150 + 3000 = 8150 gal of storage.

With 1 gph recovery at the maximum hourly meal output, the recovery required is 300 gph, with 300 × 2.0/0.7 = 860 gal of additional storage. Combining this with item *b,* the entire building requires 750 + 300 = 1050 gph recovery and 2150 + 860 = 3010 gal of storage.

Note: Recovery capacities shown are for heating water only. Additional capacity must be added to offset system heat losses.

Example 3. Determine the water-heater size and monthly hot-water consumption for an office building to be occupied by 300 people under the following conditions:
 a. Storage with minimum recovery rate
 b. Storage with 1.0 gal per person storage
 c. Additional minimum recovery rate requirement for a luncheonette open 5 days a week, serving a maximum of 100 meals per hour and an average of 200 meals per day
 d. Monthly hot-water consumption

Solution:
 a. With minimum recovery rate of 0.1 gph per person from Figure 19, 30 gph recovery is required; storage is 1.6 gal per person, or 300 × 1.6 = 480 gal. If 70% of the hot water is usable, the tank size is 480/0.7 = 690 gal.

b. The curve also shows 1.0 gal storage per person at 0.175 gph per person recovery, or 300 × 0.175 = 52.5 gph. The tank size is 300/0.7 = 430 gal.

c. Hot-water requirements for a luncheonette (Type B) are in Figure 20. With a minimum recovery capacity of 0.25 gph per maximum meals per hour, 100 meals per hour requires 25 gph recovery, and the storage is 2.0 gal per maximum meals per hour, or 100 × 2.0/0.7 = 290 gal storage. The combined requirements with item *a* are then 55 gph recovery and 980 gal storage.

Combined with item *b,* the requirement is 77.5 gph recovery and 720 gal storage.

d. Average day values are found in Table 7. The office building consumes an average of 1.0 gal per person per day × 30 days per month × 300 people = 9000 gal per month and the luncheonette will consume

0.7 gal per meal × 200 meals per day × 22 days per month = 3100 gal per month, for a total of 12,100 gal per month.

Note: Recovery capacities shown are for heating water only. Additional capacity must be added to offset the system heat losses.

Example 4. Determine the water heater size for a 200-unit apartment house under the following conditions:
 a. Storage with minimum recovery rate
 b. Storage with 4 gph per apartment recovery rate
 c. Storage for each of two 100-unit wings
  1. Minimum recovery rate
  2. Recovery rate of 4 gph per apartment

Solution:
 a. The minimum recovery rate, from Figure 21, for apartment buildings with 200 apartments is 2.1 gph per apartment, or a total of 420 gph. The storage required is 24 gal per apartment, or 4800 gal. If 70% of this hot water is usable, the necessary tank size is 4800/0.7 = 6900 gal.

b. The same curve shows 5 gal storage per apartment at a recovery rate of 4 gph per apartment, or 200 × 4 = 800 gph. The tank size is 200 × 5/0.7 = 1400 gal.

c. Solution for a 200-unit apartment house having two wings, each with its own hot-water system.
  1. With minimum recovery rate of 2.5 gph per apartment (see Figure 21), a 250 gph recovery is required, and the necessary storage is 28 gal per apartment, or 100 × 28 = 2800 gal. The required tank size is 2800/0.7 = 4000 gal for each wing.
  2. The curve shows that, for a recovery rate of 4 gph per apartment, storage is 14 gal per apartment, or 100 × 14 = 1400 gal, with recovery of 100 × 4 = 400 gph. The necessary tank size is 1400/0.7 = 2000 gal in each wing.

Note: Recovery capacities shown are for heating water only. Additional capacity must be added to offset the system heat loss.

Example 5. Determine the water-heater size and monthly hot-water consumption for a 2000-student high school under the following conditions:
 a. Storage with minimum recovery rate
 b. Storage with 4000 gal maximum storage capacity
 c. Monthly hot-water consumption

Solution:
 a. With the minimum recovery rate of 0.15 gph per student (from Figure 23) for high schools, 300 gph recovery is required. The storage required is 3.0 gal per student, or 2000 × 3.0 = 6000 gal. If 70% of the hot water is usable, the tank size is 6000/0.7 = 8600 gal.
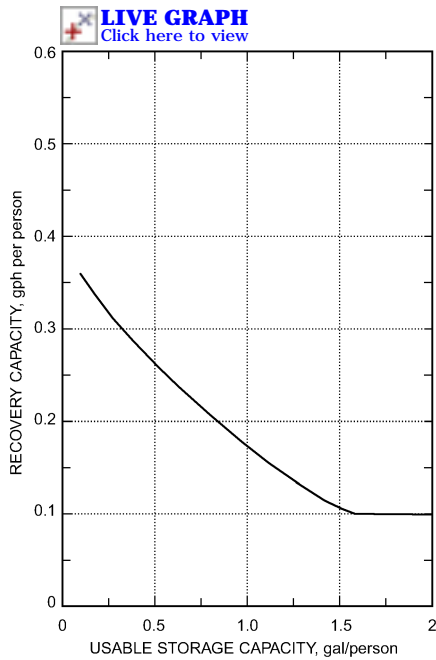
Fig. 19   Office Buildings
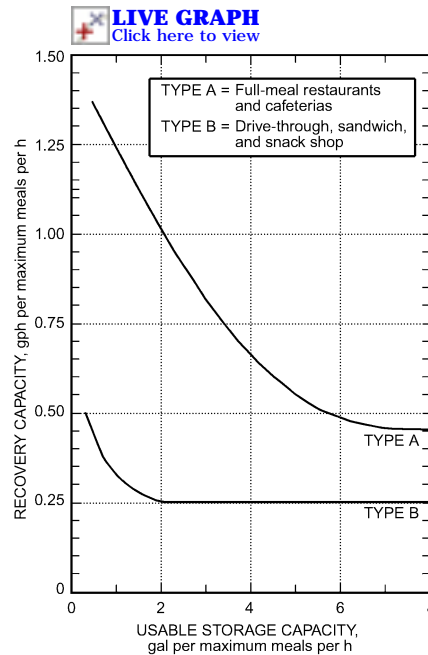
Fig. 20   Food Service

Fig. 21   Apartments

TYPE A = Full-meal restaurants and cafeterias

TYPE B = Drive-through, sandwich, and snack shop

20 OR FEWER APARTMENTS
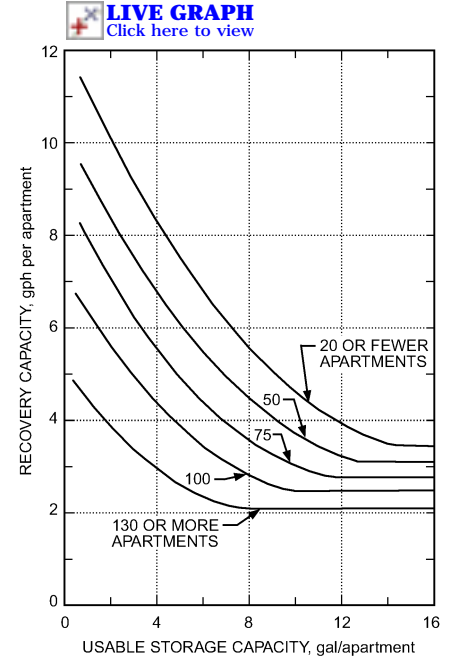
130 OR MORE APARTMENTS
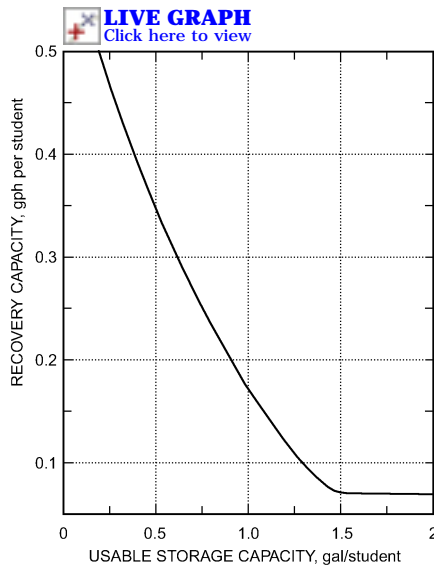
Fig. 22   Elementary Schools
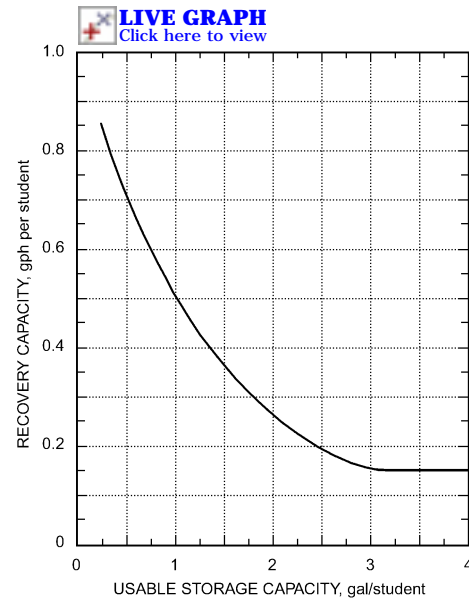
Fig. 23   High Schools

b. Net storage capacity is 0.7 × 4000 = 2800 gal, or 1.4 gal per student. From the curve, a recovery capacity of 0.37 gph per student or 2000 × 0.37 = 740 gph is required.

c. From Table 7, monthly hot-water consumption is 2000 students × 1.8 gal per student per day × 22 days = 79,000 gal.

Note: Recovery capacities shown are for heating water only. Additional capacity must be added to offset the system heat loss.

Table 10 can be used to determine the size of water-heating equipment from the number of fixtures. However, caution is advised when using this table, because its data are very old, taken well before the introduction of modern low-flow fixtures and appliances. To obtain the probable maximum demand, multiply the total quantity for the fixtures by the demand factor in line 19. Note that, as the number of fixtures becomes very small (e.g., for a water heater to serve a single small apartment), the demand (diversity) factors listed in Table 10 are no longer valid. In all cases, total demand is never less than the demand for the largest single fixture. The heater or coil

should have a water-heating capacity equal to this probable maximum demand. The storage tank should have a capacity equal to the probable maximum demand multiplied by the storage capacity factor in line 20.

Example 6. Determine heater and storage tank size for an apartment building from a number of fixtures.

Solution:

60 lavatories	×	2 gph	=	120 gph
30 bathtubs	×	20 gph	=	600 gph
30 showers	×	30 gph	=	900 gph
60 kitchen sinks	×	10 gph	=	600 gph
15 laundry tubs	×	20 gph	=	300 gph
Possible maximum demand			=	2520 gph
Probable maximum demand	=	2520 × 0.30	=	756 gph
Heater or coil capacity			=	756 gph
Storage tank capacity	=	756 × 1.25	=	945 gal
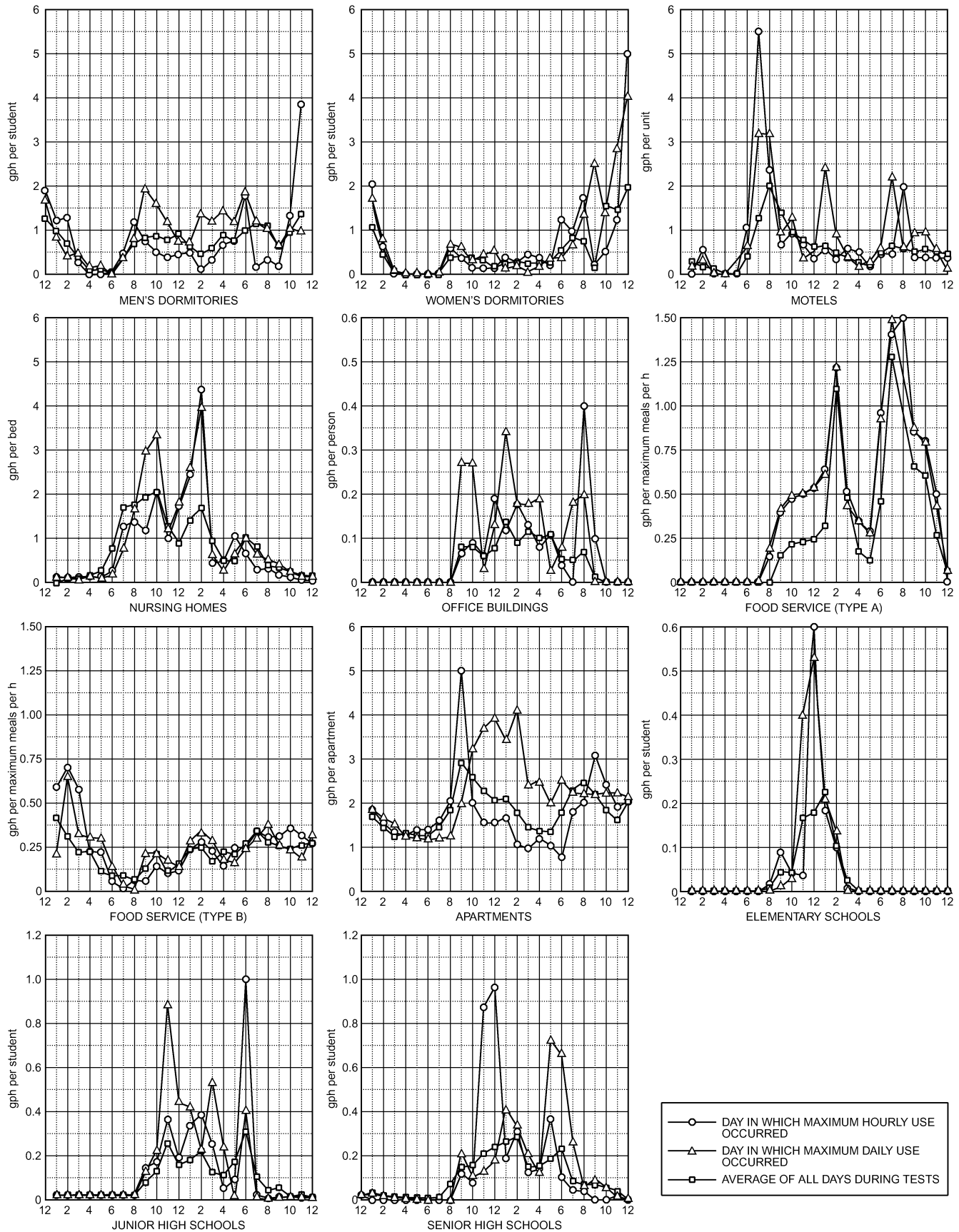
Fig. 24   Hourly Flow Profiles for Various Building Types

Table 10 Hot-Water Demand per Fixture for Various Types of Buildings

(Gallons of water per hour per fixture, calculated at a final temperature of 140°F)

	Apartment House	Club	Gymnasium	Hospital	Hotel	Industrial Plant	Office Building	Private Residence	School	YMCA
1. Basin, private lavatory	2	2	2	2	2	2	2	2	2	2
2. Basin, public lavatory	4	6	8	6	8	12	6	—	15	8
3. Bathtub[c]	20	20	30	20	20	—	—	20	—	30
4. Dishwasher[a]	15	50-150	—	50-150	50-200	20-100	—	15	20-100	20-100
5. Foot basin	3	3	12	3	3	12	—	3	3	12
6. Kitchen sink	10	20	—	20	30	20	20	10	20	20
7. Laundry, stationary tub	20	28	—	28	28	—	—	20	—	28
8. Pantry sink	5	10	—	10	10	—	10	5	10	10
9. Shower	30	150	225	75	75	225	30	30	225	225
10. Service sink	20	20	—	20	30	20	20	15	20	20
11. Hydrotherapeutic shower				400						
12. Hubbard bath				600						
13. Leg bath				100						
14. Arm bath				35						
15. Sitz bath				30						
16. Continuous-flow bath				165						
17. Circular wash sink				20	20	30	20		30	
18. Semicircular wash sink				10	10	15	10		15	
19. DEMAND FACTOR	0.30	0.30	0.40	0.25	0.25	0.40	0.30	0.30	0.40	0.40
20. STORAGE CAPACITY FACTOR[b]	1.25	0.90	1.00	0.60	0.80	1.00	2.00	0.70	1.00	1.00

Note: Data sources predate low-flow fixtures and appliances.
[a]Dishwasher requirements should be taken from this table or from manufacturers' data for model to be used, if known.

[b]Ratio of storage tank capacity to probable maximum demand/h. Storage capacity may be reduced where unlimited supply of steam is available from central street steam system or large boiler plant.
[c]Whirlpool baths require specific consideration based on capacity. They are not included in the bathtub category.

Showers. In many housing installations such as motels, hotels, and dormitories, peak hot-water load is usually from shower use. Table 10 indicates the probable hourly hot-water demand and recommended demand and storage capacity factors for various types of buildings. Hotels could have a 3 to 4 h peak shower load. Motels require similar volumes of hot water, but peak demand may last for only a 2 h period. In some types of housing, such as barracks, fraternity houses, and dormitories, all occupants may take showers within a very short period. In this case, it is best to find the peak load by determining the number of shower heads and rate of flow per head; then estimate the length of time the shower will be on. It is estimated that the average shower time per individual is 7.5 min (Meier 1985).

Flow rate from a shower head varies depending on type, size, and water pressure. At 40 psi water pressure, available shower heads have nominal flow rates of blended hot and cold water from about 2.5 to 6 gpm. In multiple-shower installations, flow control valves on shower heads are recommended because they reduce flow rate and maintain it regardless of fluctuations in water pressure. Flow can usually be reduced to 50% of the manufacturer's maximum flow rating without adversely affecting the spray pattern of the shower head. Flow control valves are commonly available with capacities from 1.5 to 4.0 gpm.

If the manufacturer's flow rate for a shower head is not available and no flow control valve is used, the following average flow rates may serve as a guide for sizing the water heater:

Small shower head	2.5 gpm
Medium shower head	4.5 gpm
Large shower head	6 gpm

Note that the maximum flow rate allowed by U.S. federal energy efficiency standards is 2.5 gpm, as of 1992. However, higher-flow-rate models are still sold.

Food Service. In restaurants, bacteria are usually killed by rinsing washed dishes with 180 to 195°F water for several seconds. In addition, an ample supply of general-purpose hot water, usually 140 to 150°F, is required for the wash cycle of dishwashers. Although a water temperature of 140°F is reasonable for dish wash-

ing in private dwellings, in public places, the NSF (e.g., *Standard* 3) or local health departments require 180 to 195°F water in the rinsing cycle. However, the NSF allows a lower temperature when certain types of machines and chemicals are used. The two-temperature hot-water requirements of food service establishments present special problems. The lower-temperature water is distributed for general use, but the 180°F water should be confined to the equipment requiring it and should be obtained by boosting the temperature. It would be dangerous to distribute 180°F water for general use. ANSI/NSF *Standard* 3-2001 covers the design of dishwashers and water heaters used by restaurants. The American Gas Association's (Dunn et al. 1959) recommended procedure for sizing water heaters for restaurants consists of determining the following:

- Types and sizes of dishwashers used (manufacturers' data should be consulted to determine the initial fill requirements of the wash tanks)
- Required quantity of general-purpose hot water
- Duration of peak hot-water demand period
- Inlet water temperature
- Type and capacity of existing water-heating system
- Type of water heating system desired

After the quantity of hot water withdrawn from the storage tank each hour has been taken into account, the following equation may be used to size the required heater(s). The general-purpose and 180 to 195°F water requirements are determined from Tables 11 and 12.

$$q_i = Q_h c_p \rho \Delta t / \eta \qquad (14)$$

where

q_i = heater input, Btu/h
Q_h = flow rate, gph
c_p = specific heat of water = 1.00 Btu/lb·°F
ρ = density of water = 8.33 lb/gal
Δt = temperature rise, °F
η = heater efficiency

To determine the quantity of usable hot water from storage, the duration of consecutive peak demand must be estimated. This peak usually coincides with the dishwashing period during and after the

Table 11 NSF Final Rinse Water Requirement for Dishwashers[a]

Type and Size of Dishwasher	Flow Rate, gpm	180 to 195°F Hot-Water Requirements	
		Heaters Without Internal Storage,[b] gph	Heaters with Internal Storage to Meet Flow Demand,[c] gph
Door type:			
16 × 16 in.	6.94	416	69
18 × 18 in.	8.67	520	87
20 × 20 in.	10.4	624	104
Undercounter	5	300	70
Conveyor type:			
Single tank	6.94	416	416
Multiple tank (dishes flat)	5.78	347	347
Multiple tank (dishes inclined)	4.62	277	277
Silver washers	7	420	45
Utensil washers	8	480	75
Makeup water requirements	2.31	139	139

Note: Values are extracted from a previous version of ANSI/NSF *Standard* 3. The current version of ANSI/NSF *Standard* 3-2001 is performance-based and no longer lists minimum flow rates.
[a]Flow pressure at dishwashers assumed to be 20 psig.
[b]Based on flow rate in gpm.
[c]Based on dishwasher operation at 100% of mechanical capacity.

Table 12 General-Purpose Hot-Water (140°F) Requirement for Various Kitchens Uses[a,b]

Equipment	gph
Vegetable sink	45
Single pot sink	30
Double pot sink	60
Triple pot sink	90
Prescrapper (open type)	180
Preflush (hand-operated)	45
Preflush (closed type)	240
Recirculating preflush	40
Bar sink	30
Lavatories (each)	5

Source: Dunn et al. (1959).
[a]Supply water pressure at equipment assumed to be 20 psig.
[b]Dishwasher operation at 100% of mechanical capacity.

main meal and may last from 1 to 4 h. Any hour in which the dishwasher is used at 70% or more of capacity should be considered a peak hour. If the peak demand lasts for 4 h or more, the value of a storage tank is reduced, unless especially large tanks are used. Some storage capacity is desirable to meet momentary high draws.

NSF *Standard* 5 recommendations for hot-water rinse demand are based on 100% operating capacity of the machines, as are the data provided in Table 11. NSF *Standard* 5 states that 70% of operating rinse capacity is all that is normally attained, except for rackless-type conveyor machines.

Examples 7, 8, and 9 demonstrate the use of Equation (14) in conjunction with Tables 11 and 12.

Example 7. Determine the hot-water demand for water heating in a cafeteria kitchen with one vegetable sink, five lavatories, one prescrapper, one utensil washer, and one two-tank conveyor dishwasher (dishes inclined) with makeup device. The initial fill requirement for the tank of the utensil washer is 85 gph at 140°F. The initial fill requirement for the dishwasher is 20 gph for each tank, or a total of 40 gph, at 140°F. The maximum period of consecutive operation of the dishwasher at or above 70% capacity is assumed to be 2 h. Supply water temperature is 60°F.

Solution: The required quantities of general-purpose (140°F) and rinse (180°F) water for the equipment, from Tables 11 and 12 and given values, are shown in the following tabulation:

Item	Quantity Required at 140°F, gph	Quantity Required at 180°F, gph
Vegetable sink	45	—
Lavatories (5)	25	—
Prescrapper	180	—
Dishwasher	—	277
Initial tank fill	40	—
Makeup water	—	139
Utensil washer	—	75
Initial tank fill	85	—
Total requirements	375	491

The total consumption of 140°F water is 375 gph. The total consumption at 180°F depends on the type of heater to be used. For a heater that has enough internal storage capacity to meet the flow demand, the total consumption of 180°F water is (277 + 139 + 75) = 491 gph based on the requirements taken from Table 11, or approximately 350 gph (0.70 × 491 = 344 gph). For an instantaneous heater without internal storage capacity, the total quantity of 180°F water consumed must be based on the flow demand. From Table 11, the quantity required for the dishwasher is 277 gph; for the makeup, 139 gph; and for the utensil washer, 480 gph. The total consumption of 180°F water is 277 + 139 + 480 = 896 gph, or approximately 900 gph.

Example 8. Determine fuel input requirements (assume 75% heater efficiency) for heating water in the cafeteria kitchen described in Example 7, by the following systems, which are among many possible solutions:
a. Separate, self-contained, storage-type heaters
b. Single instantaneous-type heater having no internal storage, to supply both 180°F and 140°F water through a mixing valve
c. Separate instantaneous-type heaters having no internal storage

Solution:
a. The temperature rise for 140°F water is 140 − 60 = 80°F. From Equation (14), the fuel input required to produce 375 gph of 140°F water with an 80°F temperature rise at 75% efficiency is about 333,000 Btu/h. One or more heaters may be selected to meet this total requirement.

From Equation (14), the fuel input required to produce 491 gph of 180°F water with a temperature rise of 180 − 60 = 120°F at 75% efficiency is 654,000 Btu/h. One or more heaters with this total requirement may be selected from manufacturers' catalogs.

b. Correct sizing of instantaneous-type heaters depends on the flow rate of the 180°F rinse water. From Example 7, the consumption of 180°F water based on the flow rate is 900 gph; consumption of 140°F water is 375 gph.

Fuel input required to produce 900 gph (277 + 480 + 139) of 180°F water with a 120°F temperature rise is 1,200,000 Btu/h. Fuel input to produce 375 gph of 140°F water with a temperature rise of 80°F is 333,000 Btu/h. Total heater requirement is 1,200,000 + 333,000 = 1,533,000 Btu/h. One or more heaters meeting this total input requirement can be selected from manufacturers' catalogs.

c. Fuel input required to produce 140°F water is the same as for solution *b*, 333,000 Btu/h. One or more heaters meeting this total requirement can be selected.

Fuel input required to produce 180°F water is also the same as in solution *b*, 1,200,000 Btu/h. One or more heaters meeting this total requirement can be selected.

Example 9. A luncheonette has purchased a door-type dishwasher that handles 16 by 16 in. racks. The existing hot-water system can supply the necessary 140°F water to meet all requirements for general-purpose use and for the booster heater that is to be installed. Determine the size of the following booster heaters operating at 75% thermal efficiency required to heat 140°F water to provide sufficient 180°F rinse water for the dishwasher:
a. Booster heater with no storage capacity
b. Booster heater with enough storage capacity to meet flow demand

Solution:
a. Because the heater is the instantaneous type, it must be sized to meet the 180°F water demand at a rated flow. From Table 11, this rated flow is 6.94 gpm, or 416 gph. From Equation (14), the required fuel input with a 40°F temperature rise is 185,000 Btu/h. A heater meeting this input requirement can be selected from manufacturers' catalogs.

b. In designing a system with a booster heater having storage capacity, the dishwasher's hourly flow demand can be used instead of the

flow demand used in solution *a*. The flow demand from Table 11 is 69 gph when the dishwasher is operating at 100% mechanical capacity. From Equation (14), with a 40°F temperature rise, the fuel input required is 30,700 Btu/h. A booster heater with this input can be selected from manufacturers' catalogs.

Estimating Procedure. Hot-water requirements for kitchens are sometimes estimated on the basis of the number of meals served (assuming eight dishes per meal). Demand for 180°F water for a dishwasher is

$$D_1 = C_1 N / \theta \qquad (15)$$

where

D_1 = water for dishwasher, gph
N = number of meals served
θ = hours of service
C_1 = 0.8 for single-tank dishwasher, 0.5 for two-tank dishwasher

Demand for water for a sink with gas burners is

$$D_2 = C_2 V \qquad (16)$$

where

D_2 = water for sink, gph
C_2 = 3
V = sink capacity (15 in. depth), gal

Demand for general-purpose hot water at 140°F is

$$D_3 = C_3 N / (\theta + 2) \qquad (17)$$

where

D_3 = general-purpose water, gph
C_3 = 1.2

Total demand is

$$D = D_1 + D_2 + D_3 \qquad (18)$$

For soda fountains and luncheonettes, use 75% of the total demand. For hotel meals or other elaborate meals, use 125%.

Schools. Service water heating in schools is needed for janitorial work, lavatories, cafeterias, shower rooms, and sometimes swimming pools.

Hot water used in cafeterias is about 70% of that usually required in a commercial restaurant serving adults and can be estimated by the method used for restaurants. Where NSF sizing is required, follow *Standard* 5.

Shower and food service loads are not ordinarily concurrent. Each should be determined separately, and the larger load should determine the size of the water heater(s) and the tank. Provision must be made to supply 180°F sanitizing rinse. The booster must be sized according to the temperature of the supply water. If feasible, the same water can be used for both needs. If the distance between the two points of need is great, a separate water heater should be used.

A separate heater system for swimming pools can be sized as outlined in the section on Swimming Pools/Health Clubs.

Domestic Coin-Operated Laundries. Small domestic machines in coin laundries or apartment house laundry rooms have a wide range of draw rates and cycle times. Domestic machines provide a wash water temperature (normal) as low as 120°F. Some manufacturers recommend a temperature of 160°F; however, the average appears to be 140°F. Hot-water sizing calculations must ensure a supply to both the instantaneous draw requirements of a number of machines filling at one time and the average hourly requirements.

The number of machines drawing at any one time varies widely; the percentage is usually higher in smaller installations. One or two

customers starting several machines at about the same time has a much sharper effect in a laundry with 15 or 20 machines than in one with 40 machines. Simultaneous draw may be estimated as follows:

1 to 11 machines	100% of possible draw
12 to 24 machines	80% of possible draw
25 to 35 machines	60% of possible draw
36 to 45 machines	50% of possible draw

Possible peak draw can be calculated from

$$F = NPV_f / T \qquad (19)$$

where

F = peak draw, gpm
N = number of washers installed
P = number of washers drawing hot water divided by N
V_f = quantity of hot water supplied to machine during hot-wash fill, gal
T = wash fill period, min

Recovery rate can be calculated from

$$R = 60 N P V_f / (\theta + 10) \qquad (20)$$

where

R = total hot water (machines adjusted to hottest water setting), gph
θ = actual machine cycle time, min

Note: ($\theta + 10$) is the cycle time plus 10 min for loading and unloading.

Commercial Laundries. Commercial laundries generally use a storage water heater. The water may be softened to reduce soap use and improve quality. The trend is toward installing high-capacity washer-extractor wash wheels, resulting in high peak demand.

Sizing Data. Laundries can normally be divided into five categories. The required hot water is determined by the weight of the material processed. Average hot-water requirements at 180°F are

Institutional	2 gal/lb·h
Commercial	2 gal/lb·h
Linen supply	2.5 gal/lb·h
Industrial	2.5 gal/lb·h
Diaper	2.5 gal/lb·h

Total weight of the material times these values give the average hourly hot-water requirements. The designer must consider peak requirements; for example, a 600 lb machine may have a 20 gpm average requirement, but the peak requirement could be 350 gpm.

In a multiple-machine operation, it is not reasonable to fill all machines at the momentary peak rate. Diversity factors can be estimated by using 1.0 of the largest machine plus the following balance:

	Total number of machines				
	2	**3 to 5**	**6 to 8**	**9 to 11**	**12 and over**
1.0 +	0.6	0.45	0.4	0.35	0.3

For example, four machines have a diversity factor of 1.0 + 0.45 = 1.45.

Types of Systems. Service water-heating systems for laundries are pressurized or vented. The pressurized system uses city water pressure, and the full peak flow rates are received by the softeners, reclaimer, condensate cooler, water heater, and lines to the wash wheels. Flow surges and stops at each operation in the cycle. A pressurized system depends on an adequate water service.

The vented system uses pumps from a vented (open) hot-water heater or tank to supply hot water. The tank's water level fluctuates from about 6 in. above the heating element to a point 12 in. from the top of the tank; this fluctuation defines the working volume. The level drops for each machine fill, and makeup water runs

continuously at the average flow rate and water service pressure during the complete washing cycle. The tank is sized to have full working volume at the beginning of each cycle. Lines and softeners may be sized for the average flow rate from the water service to the tank, not the peak machine fill rate as with a closed, pressurized system.

Waste heat exchangers have continuous flow across the heating surface at a low flow rate, with continuous heat reclamation from the wastewater and flash steam. Automatic flow-regulating valves on the inlet water manifold control this low flow rate. Rapid fill of machines increases production (i.e., more batches can be processed).

Heat Recovery. Commercial laundries are ideally suited for heat recovery because 135°F wastewater is discharged to the sewer. Fresh water can be conservatively preheated to within 15°F of the wastewater temperature for the next operation in the wash cycle. Regions with an annual average temperature of 55°F can increase to 120°F the initial temperature of fresh water going into the hot-water heater. For each 1000 gph or 8330 lb per hour of water preheated 65°F (55 to 120°F), heat reclamation and associated energy savings is 540,000 Btu/h.

Flash steam from a condensate receiving tank is often wasted to the atmosphere. Heat in this flash steam can be reclaimed with a suitable heat exchanger, to preheat makeup water to the heater by 10 to 20°F above the existing makeup temperature.

Swimming Pools/Health Clubs. The desirable temperature for swimming pools is 80°F. Most manufacturers of water heaters and boilers offer specialized models for pool heating; these include a pool temperature controller and a water bypass to prevent condensation. The water-heating system is usually installed before the return of treated water to the pool. A circulation rate to generate a change of water every 8 h for residential pools and 6 h for commercial pools is acceptable. An indirect heater, in which piping is embedded in the walls or floor of the pool, has the advantage of reduced corrosion, scaling, and condensation because pool water does not flow through the pipes, but its disadvantage is the high initial installation cost.

The installation should have a pool temperature control and a water pressure or flow safety switch. The temperature control should be installed at the inlet to the heater; the pressure or flow switch can be installed at either the inlet or outlet, depending on the manufacturer's instructions. It affords protection against inadequate water flow.

Sizing should be based on four considerations:

- Conduction through the pool walls
- Convection from the pool surface
- Radiation from the pool surface
- Evaporation from the pool surface

Except in aboveground pools and in rare cases where cold groundwater flows past the pool walls, conduction losses are small and can be ignored. Because convection losses depend on temperature differentials and wind speed, these losses can be greatly reduced by installing windbreaks such as hedges, solid fences, or buildings.

Radiation losses occur when the pool surface is subjected to temperature differentials; these frequently occur at night, when the sky temperature may be as much as 80°F below ambient air temperature. This usually occurs on clear, cool nights. During the daytime, however, an unshaded pool receives a large amount of radiant energy, often as much as 100,000 Btu/h. These losses and gains may offset each other. An easy method of controlling nighttime radiation losses is to use a floating pool cover; this also substantially reduces evaporative losses.

Evaporative losses constitute the greatest heat loss from the pool (50 to 60% in most cases). If it is possible to cut evaporative losses drastically, the pool's heating requirement may be cut by as much as 50%. A floating pool cover can accomplish this.

A pool heater with an input great enough to provide a heat-up time of 24 h would be the ideal solution. However, it may not be the most economical system for pools that are in continuous use during an extended swimming season. In this instance, a less expensive unit providing an extended heat-up period of as much as 48 h can be used. Pool water may be heated by several methods. Fuel-fired water heaters and boilers, electric boilers, tankless electric circulation water heaters, air-source heat pumps, and solar heaters have all been used successfully. Air-source heat pumps and solar heating systems are often used to extend a swimming season rather than to allow intermittent use with rapid pickup.

The following equations provide some assistance in determining the area and volume of pools.

Elliptical

Area = 3.14*AB*
A = Short radius
B = Long radius
Volume = 7.5 gal/ft^3 × Area × Average Depth

Kidney Shape

Area = 0.45*L* (*A*+*B*) (approximately)
L = Length
A = Width at one end
B = Width at other end
Volume = 7.5 gal/ft^3 × Area × Average Depth

Oval (for circular, set *L* = 0)

Area = 3.14*R*^{2} + *LW*
L = Length of straight sides
W = Width or 2*R*
R = Radius of ends
Volume = 7.5 gal/ft^3 × Area × Average Depth

Rectangular

Area = *LW*
L = Length
W = Width
Volume = 7.5 gal/ft^3 × Area × Average Depth

The following is an effective method for heating outside pools. Additional equations can be found in Chapter 4.

1. Obtain pool water capacity, in gallons.
2. Determine the desired heat pickup time in hours.
3. Determine the desired pool temperature. If not known, use 80°F.
4. Determine the average temperature of the coldest month of use.

The required heater output q_t can now be determined by the following equations:

$$q_1 = \rho c_p V(t_f - t_i)/\theta \tag{21}$$

where

q_1 = pool heat-up rate, Btu/h
ρ = density of water = 8.33 lb/gal
c_p = specific heat of water = 1.00 Btu/lb·°F
V = pool volume, gal
t_f = desired temperature (usually 80°F)
t_i = initial temperature of pool, °F
θ = pool heat-up time, h

$$q_2 = UA(t_p - t_a) \tag{22}$$

where

q_2 = heat loss from pool surface, Btu/h
U = surface heat transfer coefficient = 10.5 Btu/h·ft^2·°F
A = pool surface area, ft^2
t_p = pool temperature, °F
t_a = ambient temperature, °F

Table 13 Hot-Water Usage for Industrial Wash Fountains and Showers

	Multiple Wash Fountains		Showers	
Type	Gal of 140°F Water Required for 10 min Period[a]	Flow Rate, gpm	Gal of 140°F Water Required for 15 min Period[b]	
36 in. Circular	40	3	29.0	
Semicircular	22	4	39.0	
54 in. Circular	66	5	48.7	
Semicircular	40	6	58.0	

[a]Based on 110°F wash water and 40°F cold water at average flow rates.
[b]Based on 105°F shower water and 40°F cold water.

$$q_t = q_1 + q_2 \qquad (23)$$

Notes: These heat loss equations assume a wind velocity of 3 to 5 mph. For pools sheltered by nearby fences, dense shrubbery, or buildings, an average wind velocity of less than 3.5 mph can be assumed. In this case, use 75% of the values calculated by Equation (22). For a velocity of 5 mph, multiply by 1.25; for 10 mph, multiply by 2.0.

Because Equation (22) applies to the coldest monthly temperatures, results calculated may not be economical. Therefore, a value of one-half the surface loss plus the heat-up value yields a more viable heater output figure. Heater input then equals output divided by fuel source efficiency.

Whirlpools and Spas. Hot-water requirements for whirlpool baths and spas depend on temperature, fill rate, and total volume. Water may be stored separately at the desired temperature or, more commonly, regulated at the point of entry by blending. If rapid filling is desired, provide storage at least equal to the volume needed; fill rate can then be varied at will. An alternative is to establish a maximum fill rate and provide an instantaneous water heater that can handle the flow.

Industrial Plants. Hot water (potable) is used in industrial plants for cafeterias, showers, lavatories, gravity sprinkler tanks, and industrial processes. Employee cleanup load is usually heaviest and not concurrent with other uses. Other loads should be checked before sizing, however, to be certain that this is true.

Employee cleanup load includes (1) wash troughs or standard lavatories, (2) multiple wash sinks, and/or (3) showers. Hot-water requirements for employees using standard wash fixtures can be estimated at 1 gal of hot water for each clerical and light-industrial employee per work shift and 2 gal for each heavy-industrial worker.

For sizing purposes, the number of workers using multiple wash fountains is disregarded. Hot-water demand is based on full flow for the entire cleanup period. This usage over a 10 min period is indicated in Table 13. The shower load depends on the flow rate of the shower heads and their length of use. Table 13 may be used to estimate flow based on a 15 min period.

Water heaters used to prevent freezing in gravity sprinkler or water storage tanks should be part of a separate system. The load depends on tank heat loss, tank capacity, and winter design temperature.

Process hot-water load must be determined separately. Volume and temperature vary with the specific process. If the process load occurs at the same time as the shower or cafeteria load, the system must be sized to reflect this total demand. Separate systems can also be used, depending on the various load sizes and distance between them.

Ready-Mix Concrete. In cold weather, ready-mix concrete plants need hot water to mix the concrete so that it will not be ruined by freezing before it sets. Operators prefer to keep the mix at about 70°F by adding hot water to the cold aggregate. Usually, water at about 150°F is considered proper for cold weather. If the water temperature is too high, some of the concrete will flash set.

Table 14 Water Heater Sizing for Ready-Mix Concrete Plant
(Input and Storage Tank Capacity to Supply 150°F Water at 40°F Inlet Temperature)

Truck Capacity, yd^3	Water Heater Storage Tank Volume, gal	Time Interval Between Trucks, min*					
		50	35	25	10	5	0
		Water Heater Capacity, 1000 Btu/h					
6	430	458	612	785	1375	1830	2760
7.5	490	527	700	900	1580	2100	3150
9	560	596	792	1020	1790	2380	3580
11	640	687	915	1175	2060	2740	4120

*This table assumes 10 min loading time for each truck. Thus, for a 50 min interval between trucks, it is assumed that 1 truck/h is served. For 0 min between trucks, it is assumed that one truck loads immediately after the truck ahead has pulled away. Thus, 6 trucks/h are served. It also assumes each truck carries a 120 gal storage tank of hot water for washing down at the end of dumping the load. This hot water is drawn from the storage tank and must be added to the total hot-water demands. This has been included in the table.

Generally, 30 gal of hot water per cubic yard of concrete mix is used for sizing. To obtain the total hot-water load, this number is multiplied by the number of trucks loaded each hour and the capacity of the trucks. The hot water is dumped into the mix as quickly as possible at each loading, so ample hot-water storage or large heat exchangers must be used. Table 14 shows a method of sizing water heaters for concrete plants.

Part of the heat may be obtained by heating the aggregate bin by circulating hot water through pipe coils in the walls or sides of the bin. This can allow a lower mixing-water temperature, and the aggregate flows easily from the bins. When aggregate is not heated, it often freezes into chunks, which must be thawed before they will pass through the dump gates. If hot water is used for thawing, too much water accumulates in the aggregate, and control of the final product may vary beyond allowable limits. Therefore, jets of steam supplied by a small boiler and directed on the large chunks are often used for thawing.

Sizing Instantaneous and Semi-Instantaneous Water Heaters

The methods for sizing storage water-heating equipment should not be used for instantaneous and semi-instantaneous heaters. The following is based on the Hunter (1941) method for sizing hot- and cold-water piping, with diversity factors applied for hot water and various building types.

Fixture units (Table 15) are assigned to each fixture using hot water and totalled. Maximum hot-water demand is obtained from Figures 25 or 26 by matching total fixture units to the curve for the type of building. Special consideration should be given to applications involving periodic use of shower banks, process equipment, laundry machines, etc., as may occur in field houses, gymnasiums, factories, hospitals, and other facilities. Because these applications could have all equipment on at the same time, total hot-water capacity should be determined and added to the maximum hot-water demand from the modified Hunter curves. Often, the temperature of hot water arriving at fixtures is higher than is needed, and hot and cold water are mixed together at the fixture to provide the desired temperature. Equation (24), derived from a simple energy balance on mixing hot and cold water, shows the ratio of hot-water flow to desired end-use flow for any given hot, cold, and mixed end-use temperatures.

$$\text{Hot-water flow rate} = \frac{(\text{Mixed-temperature flow rate})(T_{mixed} - T_{cold})}{(T_{hot} - T_{cold})} \qquad (24)$$

Once the actual hot-water flow rate is known, the heater can then be selected for the total demand and total temperature rise required. For critical applications such as hospitals, multiple heaters with

Table 15   Hot-Water Demand in Fixture Units (140°F Water)

	Apartments	Club	Gymnasium	Hospital	Hotels and Dormitories	Industrial Plant	Office Building	School	YMCA
Basin, private lavatory	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Basin, public lavatory	—	1	1	1	1	1	1	1	1
Bathtub	1.5	1.5	—	1.5	1.5	—	—	—	—
Dishwasher*	1.5	Five fixture units per 250 seating capacity							
Therapeutic bath	—	—	—	5	—	—	—	—	—
Kitchen sink	0.75	1.5	—	3	1.5	3	—	0.75	3
Pantry sink	—	2.5	—	2.5	2.5	—	—	2.5	2.5
Service sink	1.5	2.5	—	2.5	2.5	2.5	2.5	2.5	2.5
Shower	1.5	1.5	1.5	1.5	1.5	3.5	—	1.5	1.5
Circular wash fountain	—	2.5	2.5	2.5	—	4	—	2.5	2.5
Semicircular wash fountain	—	1.5	1.5	1.5	—	3	—	1.5	1.5

Note: Data predate modern low-flow fixtures and appliances.   *See Water-Heating Terminology section for definition of fixture unit.
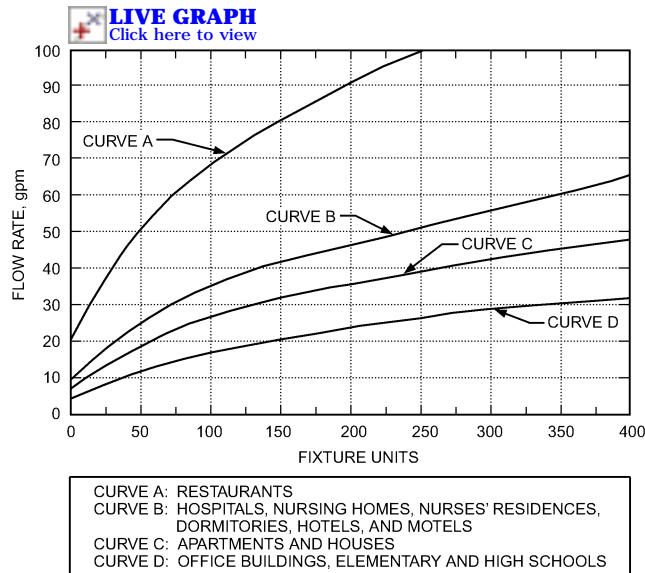
**Fig. 25   Enlarged Section of Figure 22
(Modified Hunter Curve)**
(Data predate modern low-flow fixtures and appliances)
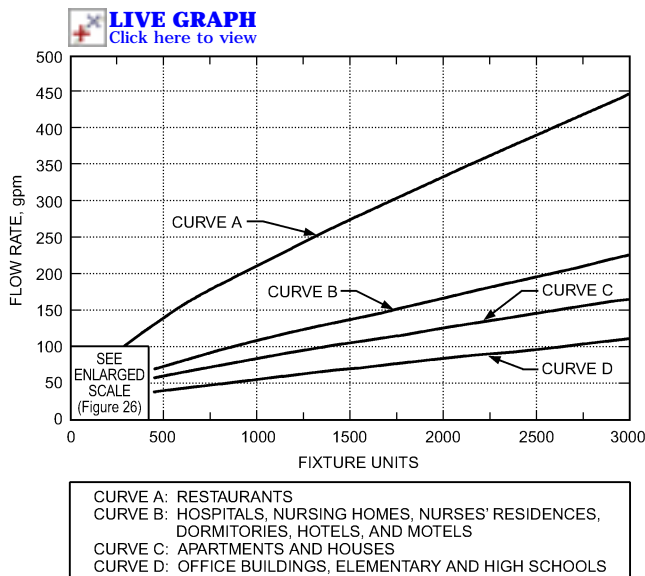
**Fig. 26   Modified Hunter Curve for Calculating
Hot-Water Flow Rate**
(Data predate modern low-flow fixtures and appliances)

Table 16   Preliminary Hot-Water Demand Estimate

Type of Building	Fixture Units
Hospital or nursing home	2.50 per bed
Hotel or motel	2.50 per room
Office building	0.15 per person
Elementary school	0.30 per student*
Junior and senior high school	0.30 per student*
Apartment house	3.00 per apartment

*Plus shower load (in fixture units).

100% standby are recommended. Consider multiple heaters for buildings in which continuity of service is important. The minimum recommended size for semi-instantaneous heaters is 10 gpm, except for restaurants, for which it is 15 gpm. When system flow is not easily determined, the heater may be sized for full flow of the piping system at a maximum speed of 600 fpm. Heaters with low flows must be sized carefully, and care should be taken in the estimation of diversity factors. Unusual hot-water requirements should be analyzed to determine whether additional capacity is required. One example is a dormitory in a military school, where all showers and lavatories are used simultaneously when students return from a drill. In this case, the heater and piping should be sized for full system flow.

Whereas the fixture count method bases heater size of the diversified system on hot-water flow, hot-water piping should be sized for full flow to the fixtures. Recirculating hot-water systems are adaptable to instantaneous heaters.

To make preliminary estimates of hot-water demand when the fixture count is not known, use Table 16 with Figure 25 or Figure 26. The result is usually higher than the demand determined from the actual fixture count. Actual heater size should be determined from Table 15. Hot-water consumption over time can be assumed to be the same as that in the section on Hot-Water Requirements and Storage Equipment Sizing.

Example 10. A 600-student elementary school has the following fixture count: 60 public lavatories, 6 service sinks, 4 kitchen sinks, 6 showers, and 1 dishwasher at 8 gpm. Determine the hot-water flow rate for sizing a semi-instantaneous heater based on the following:
a. Estimated number of fixture units
b. Actual fixture count

Solution:
a. Use Table 16 to find the estimated fixture count: 600 students × 0.3 fixture units per student = 180 fixture units. As showers are not included, Table 15 shows 1.5 fixture units per shower × 6 showers = 9 additional fixture units. The basic flow is determined from curve D of Figure 26, which shows that the total flow for 189 fixture units is 23 gpm.
b. To size the unit based on actual fixture count and Table 15, the calculation is as follows:

60	public lavatories	×	1.0	FU	=	60 FU
6	service sinks	×	2.5	FU	=	15 FU
4	kitchen sinks	×	0.75	FU	=	3 FU
6	showers	×	1.5	FU	=	9 FU
	Subtotal					87 FU

At 87 fixture units, curve D of Figure 26 shows 16 gpm, to which must be added the dishwasher requirement of 8 gpm. Thus, the total flow is 24 gpm.

Comparing the flow based on actual fixture count to that obtained from the preliminary estimate shows the preliminary estimate to be slightly lower in this case. It is possible that the preliminary estimate could have been as much as twice the final fixture count. To prevent oversizing of equipment, use the actual fixture count method to select the unit.

Sizing Refrigerant-Based Water Heaters

Refrigerant-based water heaters such as heat pump water heaters and refrigeration heat reclaim systems cannot be sized like conventional systems to meet peak loads. The seasonal and instantaneous efficiency and output of these systems vary greatly with operating conditions. Computer software that performs detailed performance simulations taking these factors into account should be used for sizing and analysis. The capacities of these systems and any related supplemental water-heating equipment should be selected to achieve a high average daily run time (typically 12 to 24 h) and the lowest combination of operating and equipment cost. Heat pump water heater installations often benefit from having a greater ratio of storage tank capacity per unit of heating capacity than for conventional water-heating equipment. Because the heat input efficiency of heat pump water heaters is dramatically higher (200 to 300%) than conventional resistance and fossil-fuel-fired equipment, energy penalties from storage tank heat loss are substantially lower for heat pump water heater systems compared to conventional systems. Larger storage capacity allows use of smaller heat pumps, often reducing total system costs. For heat pump water heaters, adequacy of the heat source and potential effect of the cooling output must be addressed.

BOILERS FOR INDIRECT WATER HEATING

When service water is heated indirectly by a space heating boiler, Figure 27 may be used to determine the additional boiler capacity required to meet the recovery demands of the domestic water heating load. Indirect heaters include immersion coils in boilers as well as heat exchangers with space-heating media.

Because the boiler capacity must meet not only the water supply requirement but also the space heating loads, Figure 27 indicates the reduction of additional heat supply for water heating if the ratio of water-heating load to space-heating load is low. This reduction is possible because

- Maximum space-heating requirements do not occur at the time of day when the maximum peak hot-water demands occur.
- Space-heating requirements are based on the lowest outside design temperature, which may occur for only a few days of the total heating season.
- An additional heat supply or boiler capacity to compensate for pickup and radiation losses is usual. The pickup load cannot occur at the same time as the peak hot-water demand because the building must be brought to a comfortable temperature before the occupants use hot water.

The factor obtained from Figure 27 is multiplied by the peak water heating load to obtain the additional boiler output capacity required.

For reduced standby losses in summer and improved efficiency in winter, step-fired modular boilers may be used. Units not in operation cool down and reduce or eliminate jacket losses. Heated
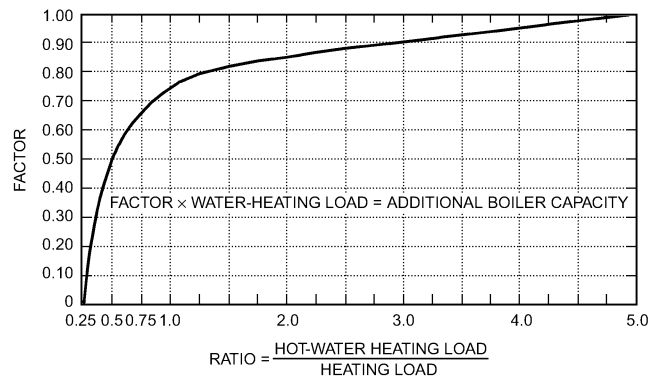
Fig. 27 Sizing Factor for Combination Heating and Water-Heating Boilers
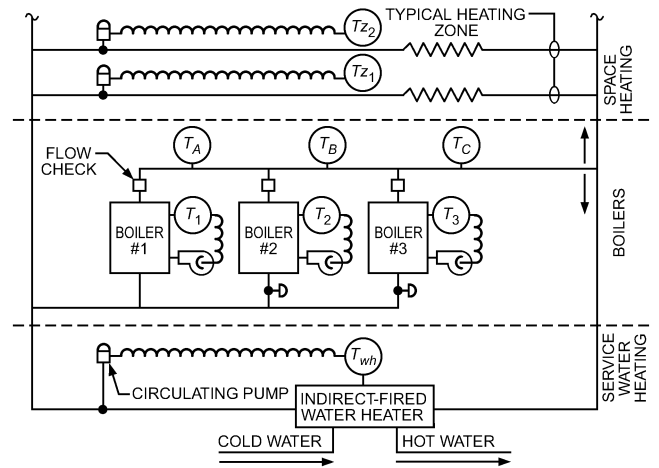
Fig. 28 Typical Modular Boiler for Combined Space and Water Heating

boiler water should not pass through an idle boiler. Figure 28 shows a typical modular boiler combination space- and water-heating arrangement.

Typical Control Sequence

1. Any control zone or indirectly fired water heater thermostat (e.g., T_{z_1} or T_{wh} in Figure 28) starts its circulating pump and supplies power to boiler No. 1 control circuit.
2. If T_1 is not satisfied, burner is turned on, boiler cycles as long as any circulating pump is on.
3. If after 5 min T_A is not satisfied, V_1 opens and boiler No. 2 comes on line.
4. If after 5 min T_B is not satisfied, V_2 opens and boiler No. 3 comes on line.
5. If T_C is satisfied and two boilers or fewer are firing for a minimum of 10 min, V_2 closes.
6. If T_B is satisfied and only one boiler is firing for a minimum of 10 min, V_1 closes.
7. If all circulating pumps are off, boiler No. 1 shuts down.

ASHRAE/IES *Standards* 90.1 and 90.2 discuss combination service water-heating/space-heating boilers and establish restrictions on their use. The ASHRAE/IES *Standard* 100 section on Service Water Heating also has information on this subject.

WATER-HEATING ENERGY USE

Energy use in water-heating systems includes the following factors, not all of which apply in a given type of system (Hiller 2006c):

- Q_{water} is energy content in water actually used, relative to entering cold-water temperature.
- $Q_{tank\ loss}$ is standby heat loss from water heater storage tank; it is proportional to time and temperature difference between water in tank and surroundings.
- $Q_{cycling\ loss}$ is energy loss from on/off cycling of heat input device, where energy invested in mass of heating device (e.g., heat exchanger) and water in it is lost to surroundings after device turns off; loss is proportional to number of heating cycles (e.g., in a tankless instantaneous water heater). Some fossil-fuel-fired tankless water heaters have pre- and/or postfiring combustion air blower operation to purge combustion products from combustion chamber, which can cause very rapid loss of invested energy in heat exchanger.
- Q_{piping} is heat energy lost from piping while water is flowing; note that, on recirculation-loop systems, heat is lost from both supply and return piping.
- $Q_{cooldown}$ is heat energy lost from piping after flow ceases; note that $Q_{cooldown}$ exhibits a large step increase once water in pipe cools to below usable temperature, because remaining warm water in pipe must be dumped to drain before usable hot water can again be obtained at fixtures; time spacing between draws and pipe insulation levels thus strongly influence this energy loss.
- Q_{dump} is energy that must be provided to reheat an amount of water equal to that dumped down the drain while waiting for hot water to arrive at fixtures; knowing the time spacing between draws in nonrecirculated piping systems is very important.
- Input efficiency η_i (tank-type water heater) or thermal efficiency η_t (tankless water heater or heating device external to tank) of heating device must be considered when calculating total water-heating system energy use.
- $Q_{circulating\ pump}$ is energy used to move water within system, if done with pumps. There are often multiple circulating pumps in system (e.g., to circulate water from storage tanks to heating devices, recirculation-loop pumps).
- $Q_{parasitics}$ is energy to operate fans, blowers, controls, and other devices.
- Q_{supply} is energy used to deliver potable water to system and force it through system. Includes pumping energy for well pumps or city water supply pumps, and water treatment system energy.
- $Q_{disposal}$ is energy used to treat and dispose of waste water, including pumping energy and other treatment system energy.

Total piping system energy use is thus

$$Q_{total} = Q_{water}/\eta_i + Q_{tank\ loss}/\eta_i + Q_{cycling\ loss} + Q_{piping}/\eta_i$$
$$+ Q_{cooldown}/\eta_i + Q_{dump}/\eta_i + Q_{circulating\ pump}$$
$$+ Q_{parasitics} + Q_{supply} + Q_{disposal}$$

Additional energy use terms may apply in some water-heating systems.

The following simple examples demonstrate how to compute water-heating system energy use for different system types and draw patterns.

Assumptions for Examples 11 to 14 include the following:

- Two fixtures 100 ft apart
- Six 5 min long draws per day of 1.0 gal/min, 105°F water at each fixture, spaced 3 min apart compared to 4 h apart
- Water heater output temperature of 120°F
- Tank-type fossil-fuel-fired water heater with input efficiency $\eta_i = 0.80$ and an energy factor of 0.59, yielding $UA_{tank} = 11.27$ Btu/h·°F, including energy input efficiency (note that tank heat loss rate is a function of energy factor rating, not tank size. However, for equal amounts of insulation, smaller tanks have higher energy factor rating)
- $T_{air} = 67.5$°F for both piping and tank
- $T_{cold} = 58$°F entering cold-water temperature

- Supply piping is 3/4 in. rigid copper with 1/2 in. thick foam insulation $(Mc_p)_{w,p,i} = 0.2542$ Btu/ft·°F, pipe volume = 0.02514 gal/ft
- Return piping is 1/2 in. rigid copper with 1/2 in. thick foam insulation (RL system only)
- For simplicity, neglect short lengths of piping between fixture branch piping and main recirculation-loop piping (or tank if at location of fixture).
- For simplicity, neglect supply and disposal energy, recirculating pump energy, and other parasitics.

Example 11. Assume a continuously running hot-water recirculation-loop system with an allowed loop temperature drop to the farthest fixture of 5°F, and assuming one fixture is near the water heater.

First, compute the recirculation loop flow rate needed to prevent temperature dropping below 115°F, using Equations (1) to (4) and (9).

$$\Delta T_{lm} = \frac{(120 - 67.5°F) - (115 - 67.5°F)}{\ln[(120 - 67.5°F)/(115 - 67.5°F)]} = 49.96°F$$

$UA_{flowing\ supply} = 0.25$ Btu/h·ft·°F (from Table 1)

$$\begin{aligned} Q_{piping\ supply} &= (0.25\ \text{Btu/h·ft·°F})(100\ \text{ft})(49.96°F)/0.8 \\ &= (1561\ \text{Btu/h})(24\ \text{h/day}) \\ &= 37{,}470\ \text{Btu/day} \end{aligned}$$

$$m_{circulating\ pump} = \frac{(1561\ \text{Btu/h})(0.8)}{(60\ \text{min/h})(8.25\ \text{lb}_m/\text{gal})(1\ \text{Btu/lb}_m·°F)(5°F)}$$

$$= 0.50\ \text{gal/min}$$

$UA_{flowing\ return} = 0.20$ Btu/h·ft·°F (from Table 1)

$$\begin{aligned} T_{hot\ return\ out} &= 67.5°F + (115 - 67.5°F) \\ &\times e^{-\left\{\frac{(0.20\ \text{Btu/h·ft·°F})(100\ \text{ft})}{(0.5\ \text{gal/min})(60\ \text{min/h})(8.25\ \text{lb}_m/\text{gal})(1\ \text{Btu/lb}_m·°F)}\right\}} \\ &= 111.31°F \end{aligned}$$

$$\begin{aligned} Q_{piping\ return} &= (0.50\ \text{gal/min})(60\ \text{min/h})(8.25\ \text{lb}_m/\text{gal}) \\ &\quad \times (1\ \text{Btu/lb}_m·°F)(115 - 111.31°F)/0.8 \\ &= (1142\ \text{Btu/h})(24\ \text{h/day}) \\ &= 27{,}408\ \text{Btu/day} \end{aligned}$$

Next, determine the amount of hot water mixed with cold water to deliver the 105°F fixture delivery temperature, from Equation (24).

For the fixture at the water heater,

$$m_{hot\ near} = (1\ \text{gal/min})(105 - 58°F)/(120 - 58°F) = 0.758\ \text{gal/min}$$

And for the far fixture,

$$m_{hot\ far} = (1\ \text{gal/min})(105 - 58°F)/(115 - 58°F) = 0.825\ \text{gal/min}$$

Consequently,

$$\begin{aligned} Q_{water\ near} &= (0.758\ \text{gal/min})(8.33\ \text{lb}_m/\text{gal})(1\ \text{Btu/lb}_m·°F) \\ &\quad \times (120 - 58°F)(5\ \text{min/draw})(6\ \text{draws/day})/0.8 \\ &= 14{,}680\ \text{Btu/day} \end{aligned}$$

$$\begin{aligned} Q_{water\ far} &= (0.825\ \text{gal/min})(8.33\ \text{lb}_m/\text{gal})(1\ \text{Btu/lb}_m·°F) \\ &\quad \times (115 - 58°F)(5\ \text{min/draw})(6\ \text{draws/day})/0.8 \\ &= 14{,}689\ \text{Btu/day} \end{aligned}$$

This is the same as for the near fixture, as it should be, because piping heat loss is separately computed.

$$\begin{aligned} Q_{tank\ heat\ loss} &= (11.27\ \text{Btu/h·°F})(120 - 67.5°F)(24\ \text{h/day}) \\ &= 14{,}200\ \text{Btu/day} \end{aligned}$$

Thus,

$Q_{total\ RL\ system}$ = 37,470 + 27,408 + 14,680 + 14,689 + 14,200

$\quad\quad\quad\quad$ = 108,447 Btu/day

With the recirculation system, energy use is the same regardless of draw spacing.

Example 12. Assume a nonrecirculated piping system, one fixture at water heater, draws 3 min and 4 h apart.

First, determine the steady-state delivery temperature at the far fixture, and the actual hot-water flow rate to that fixture. This requires iteration: guessing an initial piping outlet temperature, calculating an estimated hot-water flow rate using Equation (24), and then calculating a new piping outlet temperature based on the calculated flow rate.

Guess $T_{hot\ out\ 1}$ = 120°F. Then,

$$m_{hot\ 1} = \frac{(1.0\ \text{gal/min})(105 - 58°F)}{(120 - 58°F)}$$

$\quad\quad\quad$ = 0.758 gal/min [from Equation (24)]

$T_{hot\ out\ 2}$ = 116.6°F [from Equation (2), where

$$UA_{flowing} = 0.25\ \text{Btu/h·ft·°F}, L = 100\ \text{ft}]$$

$$m_{hot\ 2} = \frac{(1.0\ \text{gal/min})(105 - 58°F)}{(116.6 - 58°F)} = 0.80\ \text{gal/min}$$

$$T_{hot\ out\ 3} = 116.8°F$$

$$m_{hot\ 3} = \frac{(1.0\ \text{gal/min})(105 - 58°F)}{(116.8 - 58°F)} = 0.7993\ \text{gal/min}$$

$$T_{hot\ out\ 4} = 116.79°F$$

Thus,

$Q_{water\ far} + Q_{piping}$ = (0.7993 gal/min)(8.33 lb_m/gal)(1 Btu/lb_m·°F)

$\quad\quad\quad\quad\quad\quad\quad$ × (120 − 58°F)(5 min/draw)(6 draws/day)/0.8

$\quad\quad\quad\quad\quad\quad\quad$ = 15,480 Btu/day

Note that, in this computation, water energy and piping flowing heat loss energy are calculated together for simplicity.

$Q_{water\ near}$ = same as in Example 11 = 14,680 Btu/day

Next, compute the pipe temperature at the end of both the 3 min and 4 h cooldown (cd) periods, accounting for the different draw spacing scenarios. For simplicity, base the heat loss calculations on an average pipe temperature of (120 + 116.79°F)/2 = 118.4°F.

Using $UA_{zero\ flow}$ = 0.15 Btu/h·ft·°F from Table 1, and Equation (8),

$$T_{pipe\ 3\ min} = 67.5°F + (118.4 - 67.5°F)$$

$$\times\ e^{-\left\{\frac{(0.15\ \text{Btu/h·ft·°F})(3\ \text{min})}{(60\ \text{min/h})(0.2542\ \text{Btu/ft·°F})}\right\}}$$

$\quad\quad\quad\quad$ = 116.92°F

and

$$T_{pipe\ 4\ h} = 72.3°F$$

The pipe does not cool below a usable temperature with the 3 min draw spacing, but it does with the 4 h draw spacing. This means that, for the 3 min draw spacing, there are five draws with small amounts of piping cooldown between draws plus one complete cooldown for the last draw of the day, whereas for the 4 h draw spacing, there are six complete cooldowns that result in dumping water in the pipe to drain at the next draw. Because pipe length to the fixture at the water heater is essentially zero under the assumptions here, only draws at the far fixture result in piping energy loses.

From Equation (5),

$Q_{cd\ 3\ min}$ = (0.2542 Btu/ft·°F)(100 ft)(118.4 − 116.92°F)

$\quad\quad\quad\quad$ × 5 cd/day/0.8 + 1 cd (lumped into Q_{dump})

$\quad\quad\quad\quad$ = 235 Btu/day

To estimate Q_{dump} and the amount of water waste, assume an AF/PV ratio of 1.5. Thus, each time the pipe cools below a usable temperature, (1.5)(0.02514 gal/ft)(100 ft) = 3.77 gal of water must be dumped to drain.

$Q_{dump\ 3\ min}$ = (1 dump/day)(3.77 gal/dump)(8.33 lb_m/gal)

$\quad\quad\quad\quad$ × (1 Btu/lb_m·°F)(120 − 58°F)/0.8

$\quad\quad\quad\quad$ = 2434 Btu/day

$Q_{dump\ 4\ h}$ = (6 dumps/day)(2434 Btu/dump) = 14,604 Btu/day

and

$$Q_{cd\ 4\ h} = 0$$

because all cooldown energy is lumped into Q_{dump}.

$$Q_{tank\ heat\ loss} = 14{,}200\ \text{Btu/day, as in Example 11}$$

To simplify calculation of total water-heating system energy use, it is convenient to add the cooldown energy term computed as shown to the Q_{water} term calculated as if all hot water were delivered to the fixture at a constant flow rate and the steady-state temperature. In reality, the hot-water flow rate to the fixture varies during the initial part of a draw as the cooled but still usable water temperature increases to the steady-state value as flow progresses. The energy use thus computed will be mathematically correct either way.

$Q_{total\ non\text{-}RL,\ 3\ min\ spacing}$ = 15,480 + 14,680 + 235 + 2434 + 14,200

$\quad\quad\quad\quad\quad\quad\quad$ = 47,033 Btu/day

$Q_{total\ non\text{-}RL,\ 4\ h\ spacing}$ = 15,480 + 14,680 + 0 + 14,604 + 14,200

$\quad\quad\quad\quad\quad\quad\quad$ = 58,968 Btu/day

Note the large increase in energy use when draws are spaced far enough apart for the pipe to cool to below a usable temperature between draws. Also, the time spent waiting for hot water to arrive at the far fixture is

$$t_{wait} = (3.77\ \text{gal})/(1\ \text{gal/min}) = 3.77\ \text{min}$$

Example 13. Assume two full-sized water heaters, one at each fixture; no piping.

In this case, tank heat loss is doubled, but piping heat loss is eliminated.

$$Q_{water} = (2)(14{,}680\ \text{Btu/day}) = 29{,}360\ \text{Btu/day}$$

$$Q_{tank\ heat\ loss} = (2)(14{,}200\ \text{Btu/day}) = 28{,}400\ \text{Btu/day}$$

$$Q_{total\ 2\text{-}tank} = 29{,}360 + 28{,}400 = 57{,}760\ \text{Btu/day}$$

Draw spacing is irrelevant to the two-tank system because there is no piping.

Example 14. Assume two smaller water heaters, one at each fixture; no piping.

When two separate water heaters are used, each can be smaller than if one water heater were used. Assuming a smaller tank-type fossil-fuel-fired water heater with input efficiency η_i = 0.80 and an energy factor of 0.61, yielding UA_{tank} = 9.86 Btu/h·°F, including energy input efficiency,

$$Q_{water} = (2)(14{,}680\ \text{Btu/day}) = 29{,}360\ \text{Btu/day}$$

$Q_{tank\ heat\ loss}$ = (2)(9.86 Btu/h·°F)(120 − 67.5°F)(24 h/day)

$\quad\quad\quad\quad$ = 24,847 Btu/day

$$Q_{total\ 2\text{-}tank} = 29{,}360 + 24{,}847 = 54{,}207\ \text{Btu/day}$$

Again, draw spacing is irrelevant to the two-tank system because there is no piping.

Table 17 Results Comparisons for Examples 11 to 14

System Type	3 min Draw Spacing			4 h Draw Spacing		
	Energy Use, Btu/day	Energy Use Compared to One Tank, %	Water Waste, gal/day	Energy Use, Btu/day	Energy Use Compared to One Tank, %	Water Waste, gal/day
Recirculation loop	108,447	231	0	108,447	184	0
One-tank	47,033	100	3.8	58,968	100	22.6
Two-tank (large)	57,760	123	0	57,760	98	0
Two-tank (small)	54,207	115	0	54,207	92	0

Table 17 compares water and energy use of Examples 11 to 14, and shows that the continuously running recirculation-loop system uses substantially more energy than the other approaches (on the order of twice as much). This is not uncommon. Also note that, in these examples, the two-tank approach saves both water waste and energy. The multiple-water-heater approach has at worst only a small negative energy effect if done properly, and under real water draw scenarios usually uses less energy than other options. This is why multiple-water-heater design options should always be considered. In some cases, multiple-water-heater systems can have lower first costs than alternatives. Note that multiple-water-heater systems can use different types of water heaters for different parts of the system: fossil-fuel-fired or heat pump water heaters can be used to serve larger loads, whereas electric resistance water heaters may be preferred for serving smaller loads. In some cases, space limitations, life and maintenance issues, and other factors may make multiple-water-heater systems unattractive.

Both simplified and detailed computer models (Hiller 1992, 2000) are available to help calculate water heater energy use. These are especially useful for analyzing the energy used by heat pump water heaters, where efficiency and heating capacity vary strongly with both source (e.g., air, water) and sink (water) temperature.

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CHAPTER 50

SNOW MELTING AND FREEZE PROTECTION

THE practicality of melting snow or ice by supplying heat to the exposed surface has been demonstrated in many installations, including sidewalks, roadways, ramps, bridges, access ramps, and parking spaces for the handicapped, and runways. Melting eliminates the need for snow removal by chemical means, provides greater safety for pedestrians and vehicles, and reduces the labor and cost of slush removal. Other advantages include eliminating piled snow, reducing liability, and reducing health risks of manual and mechanized shoveling.

This chapter covers three types of snow-melting and freeze protection systems:

1. Hot fluid circulated in slab-embedded pipes (**hydronic**)
2. Embedded **electric** heater cables or wire
3. Overhead high-intensity **infrared** radiant heating

Detailed information about slab heating can be found in Chapter 6 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*. More information about infrared heating can be found in Chapter 15 of the same volume.

Components of the system design include (1) heat requirement, (2) slab design, (3) control, and (4) hydronic or electric system design.

HYDRONIC AND ELECTRIC SNOW-MELTING SYSTEMS

SNOW-MELTING HEAT FLUX REQUIREMENT

The heat required for snow melting depends on five atmospheric factors: (1) rate of snowfall, (2) snowfall-coincident air dry-bulb temperature, (3) humidity, (4) wind speed near the heated surface, and (5) apparent sky temperature. The dimensions of the snow-melting slab affect heat and mass transfer rates at the surface. Other factors such as back and edge heat losses must be considered in the complete design.

Heat Balance

The processes that establish the heat requirement at the snow-melting surface can be described by terms in the following equation, which is the steady-state energy balance for required total heat flux (heat flow rate per unit surface area) q_o at the upper surface of a snow-melting slab during snowfall.

$$q_o = q_s + q_m + A_r(q_h + q_e) \tag{1}$$

where
q_o = heat flux required at snow-melting surface, Btu/h·ft^2
q_s = sensible heat flux, Btu/h·ft^2

The preparation of this chapter is assigned to TC 6.5, Radiant and Convective Space Heating and Cooling.

q_m = latent heat flux, Btu/h·ft^2
A_r = snow-free area ratio, dimensionless
q_h = convective and radiative heat flux from snow-free surface, Btu/h·ft^2
q_e = heat flux of evaporation, Btu/h·ft^2

Sensible and Latent Heat Fluxes. The sensible heat flux q_s is the heat flux required to raise the temperature of snow falling on the slab to the melting temperature plus, after the snow has melted, to raise the temperature of the liquid to the assigned temperature t_f of the liquid film. The snow is assumed to fall at air temperature t_a. The latent heat flux q_m is the heat flux required to melt the snow. Under steady-state conditions, both q_s and q_m are directly proportional to the snowfall rate s.

Snow-Free Area Ratio. Sensible and latent (melting) heat fluxes occur on the entire slab during snowfall. On the other hand, heat and mass transfer at the slab surface depend on whether there is a snow layer on the surface. Any snow accumulation on the slab acts to partially insulate the surface from heat losses and evaporation. The insulating effect of partial snow cover can be large. Because snow may cover a portion of the slab area, it is convenient to think of the insulating effect in terms of an effective or equivalent snow-covered area A_s, which is perfectly insulated and from which no evaporation and heat transfer occurs. The balance is then considered to be the equivalent snow-free area A_f. This area is assumed to be completely covered with a thin liquid film; therefore, both heat and mass transfer occur at the maximum rates for the existing environmental conditions. It is convenient to define a dimensionless **snow-free area ratio** A_r:

$$A_r = \frac{A_f}{A_t} \tag{2}$$

where
A_f = equivalent snow-free area, ft^2
A_s = equivalent snow-covered area, ft^2
$A_t = A_f + A_s$ = total area, ft^2

Therefore,

$$0 \le A_r \le 1$$

To satisfy $A_r = 1$, the system must melt snow rapidly enough that no accumulation occurs. For $A_r = 0$, the surface is covered with snow of sufficient thickness to prevent heat and evaporation losses. Practical snow-melting systems operate between these limits. Earlier studies indicate that sufficient snow-melting system design information is obtained by considering three values of the free area ratio: 0, 0.5, and 1.0 (Chapman 1952).

Heat Flux because of Surface Convection, Radiation, and Evaporation. Using the snow-free area ratio, appropriate heat and mass transfer relations can be written for the snow-free fraction of the slab A_r. These appear as the third and fourth terms on the right-hand side of Equation (1). On the snow-free surface, maintained at

film temperature t_f, heat is transferred to the surroundings and mass is transferred from the evaporating liquid film. Heat flux q_h includes convective losses to the ambient air at temperature t_a and radiative losses to the surroundings, which are at mean radiant temperature T_{MR}. The convection heat transfer coefficient is a function of wind speed and a characteristic dimension of the snow-melting surface. This heat transfer coefficient is also a function of the thermodynamic properties of the air, which vary slightly over the temperature range for various snowfall events. The mean radiant temperature depends on air temperature, relative humidity, cloudiness, cloud altitude, and whether snow is falling.

The heat flux q_e from surface film evaporation is equal to the evaporation rate multiplied by the heat of vaporization. The evaporation rate is driven by the difference in vapor pressure between the wet surface of the snow-melting slab and the ambient air. The evaporation rate is a function of wind speed, a characteristic dimension of the slab, and the thermodynamic properties of the ambient air.

Heat Flux Equations

Sensible Heat Flux. The sensible heat flux q_s is given by the following equation:

$$q_s = \rho_{water} s[c_{p,ice}(t_s - t_a) + c_{p,water}(t_f - t_s)]/c_1 \qquad (3)$$

where

$c_{p,ice}$ = specific heat of ice, Btu/lb·°F
$c_{p,water}$ = specific heat of water, Btu/lb·°F
s = snowfall rate water equivalent, in/h
t_a = ambient temperature coincident with snowfall, °F
t_f = liquid film temperature, °F
t_s = melting temperature, °F
ρ_{water} = density of water, lb/ft^3
c_1 = 12 in/ft

The density of water, specific heat of ice, and specific heat of water are approximately constant over the temperature range of interest and are evaluated at 32°F. The ambient temperature and snowfall rate are available from weather data. The liquid film temperature is usually taken as 33°F.

Melting Heat Flux. The heat flux q_m required to melt the snow is given by the following equation:

$$q_m = \rho_{water} s h_{if} / c_1 \qquad (4)$$

where h_{if} = heat of fusion of snow, Btu/lb.

Convective and Radiative Heat Flux from a Snow-Free Surface. The corresponding heat flux q_h is given by the following equation:

$$q_h = h_c(t_f - t_a) + \sigma \varepsilon_s (T_f^4 - T_{MR}^4) \qquad (5)$$

where

h_c = convection heat transfer coefficient for turbulent flow, Btu/h·ft^2·°F
T_f = liquid film temperature, °R
T_{MR} = mean radiant temperature of surroundings, °R
σ = Stefan-Boltzmann constant = 0.1712 × 10^{-8} Btu/h·ft^2·°R^4
ε_s = emittance of surface, dimensionless

The convection heat transfer coefficient over the slab on a plane horizontal surface is given by the following equations (Incropera and DeWitt 1996):

$$h_c = 0.037\left(\frac{k_{air}}{L}\right)\text{Re}_L^{0.8}\text{Pr}^{1/3} \qquad (6)$$

where

k_{air} = thermal conductivity of air at t_a, Btu·ft/h·ft^2·°F

L = characteristic length of slab in direction of wind, ft
Pr = Prandtl number for air, taken as Pr = 0.7
Re$_L$ = Reynolds number based on characteristic length L

and

$$\text{Re}_L = \frac{VL}{\nu_{air}}c_2 \qquad (7)$$

where

V = design wind speed near slab surface, mph
ν_{air} = kinematic viscosity of air, ft^2/h
c_2 = 5280 ft/mile

Without specific wind data for winter, the extreme wind data in Chapter 28 of the 2005 *ASHRAE Handbook—Fundamentals* may be used; however, it should be noted that these wind speeds may not correspond to actual measured data. If the snow-melting surface is not horizontal, the convection heat transfer coefficient might be different, but in many applications, this difference is negligible.

From Equations (6) and (7), it can be seen that the turbulent convection heat transfer coefficient is a function of $L^{-0.2}$. Because of this relationship, shorter snow-melting slabs have higher convective heat transfer coefficients than longer slabs. For design, the shortest dimension should be used (e.g., for a long, narrow driveway or sidewalk, use the width). A snow-melting slab length L = 20 ft is used in the heat transfer calculations that resulted in Tables 1, 2, and 3.

The **mean radiant temperature** T_{MR} in Equation (5) is the equivalent blackbody temperature of the surroundings of the snow-melting slab. Under snowfall conditions, the entire surroundings are approximately at the ambient air temperature (i.e., $T_{MR} = T_a$). When there is no snow precipitation (e.g., during idling and after snowfall operations for $A_r < 1$), the mean radiant temperature is approximated by the following equation:

$$T_{MR} = \left[T_{cloud}^4 F_{sc} + T_{sky\ clear}^4(1 - F_{sc})\right]^{1/4} \qquad (8)$$

where

F_{sc} = fraction of radiation exchange that occurs between slab and clouds
T_{cloud} = temperature of clouds, °R
$T_{sky\ clear}$ = temperature of clear sky, °R

The equivalent blackbody temperature of a clear sky is primarily a function of the ambient air temperature and the water content of the atmosphere. An approximation for the clear sky temperature is given by the following equation, which is a curve fit of data in Ramsey et al. (1982):

$$T_{sky\ clear} = T_a - (1.99036 \times 10^3 - 7.562T_a$$
$$+ 7.407 \times 10^{-3}T_a^2 - 56.325\phi + 26.25\phi^2) \qquad (9)$$

where

T_a = ambient temperature, °R
ϕ = relative humidity of air at elevation for which typical weather measurements are made, decimal

The cloud-covered portion of the sky is assumed to be at T_{cloud}. The height of the clouds may be assumed to be 10,000 ft. The temperature of the clouds at 10,000 ft is calculated by subtracting the product of the average lapse rate (rate of decrease of atmospheric temperature with height) and the altitude from the atmospheric temperature T_a. The average lapse rate, determined from the tables of U.S. Standard Atmospheres (COESA 1976), is 3.5°F per 1000 ft of elevation (Ramsey et al. 1982). Therefore, for clouds at 10,000 ft,

$$T_{cloud} = T_a - 35 \qquad (10)$$

Under most conditions, this method of approximating the temperature of the clouds provides an acceptable estimate. However, when the atmosphere contains a very high water content, the temperature calculated for a clear sky using Equation (9) may be warmer than the cloud temperature estimated using Equation (10). When that condition exists, T_{cloud} is set equal to the calculated clear sky temperature $T_{sky\ clear}$.

Evaporation Heat Flux. The heat flux q_e required to evaporate water from a wet surface is given by

$$q_e = \rho_{dry\ air} h_m (W_f - W_a) h_{fg} \qquad (11)$$

where

h_m = mass transfer coefficient, ft/h
W_a = humidity ratio of ambient air, lb_{vapor}/lb_{air}
W_f = humidity ratio of saturated air at film surface temperature, lb_{vapor}/lb_{air}
h_{fg} = heat of vaporization (enthalpy difference between saturated water vapor and saturated liquid water), Btu/lb
$\rho_{dry\ air}$ = density of dry air, lb/ft^3

Determination of the mass transfer coefficient is based on the analogy between heat transfer and mass transfer. Details of the analogy are given in Chapter 5 of the 2005 *ASHRAE Handbook—Fundamentals*. For external flow where mass transfer occurs at the convective surface and the water vapor component is dilute, the following equation relates the mass transfer coefficient h_m to the heat transfer coefficient h_c [Equation (6)]:

$$h_m = \left(\frac{Pr}{Sc}\right)^{2/3} \frac{h_c}{\rho_{dry\ air} c_{p,air}} \qquad (12)$$

where Sc = Schmidt number. In applying Equation (11), the values Pr = 0.7 and Sc = 0.6 were used to generate the values in Tables 1 through 4.

The humidity ratios both in the atmosphere and at the surface of the water film are calculated using the standard psychrometric relation given in the following equation (from Chapter 6 of the 2005 *ASHRAE Handbook—Fundamentals*):

$$W = 0.622\left(\frac{p_v}{p - p_v}\right) \qquad (13)$$

where

p = atmospheric pressure, psi
p_v = partial pressure of water vapor, psi

The atmospheric pressure in Equation (13) is corrected for altitude using the following equation (Kuehn et al. 1998):

$$p = p_{std}\left(1 - \frac{Az}{T_o}\right)^{5.265} \qquad (14)$$

where

p_{std} = standard atmospheric pressure, psi
A = 0.00356°R/ft
z = altitude of the location above sea level, ft
T_o = 518.7°R

Altitudes of specific locations are found in Chapter 28 of the 2005 *ASHRAE Handbook—Fundamentals*.

The vapor pressure p_v for the calculation of W_a is equal to the saturation vapor pressure p_s at the dew-point temperature of the air. Saturated conditions exist at the water film surface. Therefore, the vapor pressure used in calculating W_f is the saturation pressure at the film temperature t_f. The saturation partial pressures of water vapor for temperatures above and below freezing are found in tables of the thermodynamic properties of water at saturation or can

be calculated using appropriate equations. Both are presented in Chapter 6 of the 2005 *ASHRAE Handbook—Fundamentals*.

Heat Flux Calculations. Equations (1) to (14) can be used to determine the required heat fluxes of a snow-melting system. However, calculations must be made for coincident values of snowfall rate, wind speed, ambient temperature, and dew-point temperature (or another measure of humidity). By computing the heat flux for each snowfall hour over a period of several years, a frequency distribution of hourly heat fluxes can be developed. Annual averages or maximums for climatic factors should never be used in sizing a system because they are unlikely to coexist. Finally, it is critical to note that the preceding analysis only describes what is happening at the upper surface of the snow-melting surface. Edge losses and back losses have not been taken into account.

Example 1. During the snowfall that occurred during the 8 PM hour on December 26, 1985, in the Detroit metropolitan area, the following simultaneous conditions existed: air dry-bulb temperature = 17°F, dew-point temperature = 14°F, wind speed = 19.7 mph, and snowfall rate = 0.10 in. of liquid water equivalent per hour. Assuming L = 20 ft, Pr = 0.7, and Sc = 0.6, calculate the surface heat flux q_o for a snow-free area ratio of A_r = 1.0. The thermodynamic and transport properties used in the calculation are taken from Chapters 6 and 39 of the 2005 *ASHRAE Handbook—Fundamentals*. The emittance of the wet surface of the heated slab is 0.9.

Solution:

By Equation (3),

$$q_s = 62.4 \times \frac{0.10}{12}[0.49(32-17)+1.0(33-32)] = 4.3 \text{ Btu/h} \cdot \text{ft}^2$$

By Equation (4),

$$q_m = 62.4 \times \frac{0.10}{12} \times 143.3 = 74.5 \text{ Btu/h} \cdot \text{ft}^2$$

By Equation (7),

$$Re_L = \frac{19.7 \times 20 \times 5280}{0.49} = 4.24 \times 10^6$$

By Equation (6),

$$h_c = 0.037\left(\frac{0.0135}{20}\right)(4.24 \times 10^6)^{0.8}(0.7)^{1/3} = 4.44 \text{ Btu/h} \cdot \text{ft}^2 \cdot \text{°F}$$

By Equation (5),

$$q_h = 4.44(33-17) + (0.1712 \times 10^{-8})(0.9)(493^4 - 477^4)$$

$$= 83.5 \text{ Btu/h} \cdot \text{ft}^2$$

By Equation (12),

$$h_m = \left(\frac{0.7}{0.6}\right)^{2/3} \frac{4.44}{0.083 \times 0.24} = 247 \text{ ft/h}$$

Obtain the values of the saturation vapor pressures at the dew-point temperature 14°F and the film temperature 33°F from Table 3 in Chapter 6 of the 2005 *ASHRAE Handbook—Fundamentals*. Then, use Equation (13) to obtain W_a = 0.00160 lb_{vapor}/lb_{air} and W_f = 0.00393 lb_{vapor}/lb_{air}. By Equation (11),

$$q_e = 0.083 \times 247(0.00393 - 0.00160) \times 1075 = 51.3 \text{ Btu/h} \cdot \text{ft}^2$$

By Equation (1),

$$q_o = 4.3 + 74.5 + 1.0(83.5 + 51.3)$$

$$= 214 \text{ Btu/h} \cdot \text{ft}^2 \times 0.2931 = 62.7 \text{ W/ft}^2$$

Note that this is the heat flux needed at the snow-melting surface of the slab. Back and edge losses must be added as discussed in the section on Back and Edge Heat Losses.

Table 1   Frequencies of Snow-Melting Surface Heat Fluxes at Steady-State Conditions[a]

Location	Snowfall Hours per Year	Snow-Free Area Ratio, A_r	Heat Fluxes Not Exceeded During Indicated Percentage of Snowfall Hours from 1982 Through 1993, Btu/h·ft[2 b]					
			75%	90%	95%	98%	99%	100%
Albany, NY	156	1	89	125	149	187	212	321
		0.5	60	86	110	138	170	276
		0	37	62	83	119	146	276
Albuquerque, NM	44	1	70	118	168	191	242	393
		0.5	51	81	96	117	156	229
		0	30	46	61	89	92	194
Amarillo, TX	64	1	113	150	168	212	228	318
		0.5	71	88	108	124	142	305
		0	24	46	62	89	115	292
Billings, MT	225	1	112	164	187	212	237	340
		0.5	64	89	102	116	128	179
		0	22	33	45	60	68	113
Bismarck, ND	158	1	151	199	231	275	307	477
		0.5	83	107	124	148	165	243
		0	16	30	39	60	73	180
Boise, ID	85	1	58	79	100	126	146	203
		0.5	38	52	66	80	89	164
		0	22	31	40	53	62	164
Boston, MA	112	1	96	137	165	202	229	365
		0.5	65	95	112	149	190	365
		0	37	75	93	121	172	365
Buffalo, NY	292	1	115	166	210	277	330	570
		0.5	68	97	127	164	188	389
		0	23	39	55	93	112	248
Burlington, VT	204	1	91	130	154	184	200	343
		0.5	58	78	92	113	128	343
		0	23	40	55	78	94	343
Cheyenne, WY	224	1	119	172	201	229	261	354
		0.5	70	97	111	132	149	288
		0	16	37	52	77	100	285
Chicago, IL, O'Hare International Airport	124	1	96	126	153	186	235	521
		0.5	58	77	94	113	137	265
		0	23	38	53	75	83	150
Cleveland, OH	188	1	85	124	157	195	230	432
		0.5	52	73	92	118	147	235
		0	23	37	47	69	92	225
Colorado Springs, CO	159	1	89	135	167	202	219	327
		0.5	57	82	99	124	140	218
		0	23	45	61	87	112	165
Columbus, OH, International Airport	92	1	71	101	123	149	175	328
		0.5	45	60	71	87	95	184
		0	15	30	45	60	62	135
Des Moines, IA	127	1	120	174	208	255	289	414
		0.5	74	102	120	149	180	310
		0	24	46	69	94	108	231
Detroit, MI, Metro Airport	153	1	92	130	156	192	212	360
		0.5	57	77	94	118	134	227
		0	23	38	47	75	89	194
Duluth, MN	238	1	123	171	201	238	250	370
		0.5	71	97	114	131	142	213
		0	22	32	46	68	77	196
Ely, NV	153	1	67	97	116	134	162	242
		0.5	44	66	83	111	129	241
		0	23	45	67	97	112	240
Eugene, OR	18	1	59	110	139	165	171	224
		0.5	47	77	93	119	122	164
		0	30	53	70	102	120	164
Fairbanks, AK	288	1	91	121	144	174	202	391
		0.5	52	68	78	94	108	200
		0	15	23	31	40	48	87
Baltimore, MD, BWI Airport	56	1	87	139	172	235	282	431
		0.5	69	108	147	200	238	369
		0	46	84	119	181	214	306
Great Falls, MT	233	1	123	171	193	233	276	392
		0.5	71	93	107	129	144	210
		0	17	31	45	60	75	143
Indianapolis, IN	96	1	95	134	158	194	215	284
		0.5	58	80	96	116	124	209
		0	23	38	52	83	99	209

[a]Heat fluxes are at the snow-melting surface only. See text for calculation of back and edge heat loss fluxes.   [b]Multiply values by 0.2931 to convert to W/ft^{2}.

Table 1 Frequencies of Snow-Melting Surface Heat Fluxes at Steady-State Conditions[a] (*Continued*)

Location	Snowfall Hours per Year	Snow-Free Area Ratio, A_r	Heat Fluxes Not Exceeded During Indicated Percentage of Snowfall Hours from 1982 Through 1993, Btu/h·ft^2 [b]					
			75%	90%	95%	98%	99%	100%
Lexington, KY	50	1	81	108	123	150	170	233
		0.5	49	65	74	85	95	197
		0	16	30	39	46	55	162
Madison, WI	161	1	99	138	164	206	241	449
		0.5	61	82	98	129	163	245
		0	23	39	60	91	113	194
Memphis, TN	13	1	106	141	172	200	206	213
		0.5	75	96	115	118	130	157
		0	40	75	76	90	97	123
Milwaukee, WI	161	1	101	135	164	196	207	431
		0.5	62	83	101	128	147	246
		0	23	46	68	98	120	239
Minneapolis-St. Paul, MN	199	1	119	169	193	229	254	332
		0.5	73	99	114	138	154	287
		0	23	45	61	91	113	245
New York, NY, JFK Airport	61	1	91	134	164	207	222	333
		0.5	63	93	118	145	164	325
		0	38	68	86	113	133	316
Oklahoma City, OK	35	1	117	168	215	248	260	280
		0.5	72	101	123	133	144	208
		0	24	46	68	78	113	190
Omaha, NE	94	1	108	148	189	222	259	363
		0.5	65	89	105	128	135	186
		0	23	38	60	90	100	136
Peoria, IL	91	1	95	139	166	201	227	436
		0.5	58	83	99	119	130	250
		0	23	38	53	76	92	228
Philadelphia, PA, International Airport	56	1	94	129	154	208	246	329
		0.5	65	90	112	162	185	267
		0	38	63	79	111	150	225
Pittsburgh, PA, International Airport	168	1	83	125	159	194	219	423
		0.5	51	75	94	111	129	216
		0	16	31	46	68	77	136
Portland, ME	157	1	120	168	195	234	266	428
		0.5	76	108	132	168	199	376
		0	39	67	90	130	152	324
Portland, OR	15	1	50	78	102	177	239	296
		0.5	39	55	81	114	130	199
		0	23	45	60	78	102	128
Rapid City, SD	177	1	139	203	252	312	351	482
		0.5	78	111	132	164	183	245
		0	16	30	38	53	65	179
Reno, NV	63	1	50	72	89	116	137	191
		0.5	36	55	75	105	115	172
		0	23	45	68	91	113	159
Salt Lake City, UT	142	1	52	77	89	110	120	171
		0.5	39	62	76	96	104	171
		0	30	60	75	89	104	171
Sault Ste. Marie, MI	425	1	112	153	183	216	249	439
		0.5	66	88	104	125	142	239
		0	23	37	47	68	83	188
Seattle, WA	27	1	56	107	138	171	205	210
		0.5	45	72	97	122	133	175
		0	37	52	75	96	123	151
Spokane, WA	144	1	67	98	116	141	159	227
		0.5	45	61	73	84	95	145
		0	23	37	45	54	67	112
Springfield, MO	58	1	110	155	179	215	224	292
		0.5	70	95	117	142	171	240
		0	32	54	76	115	129	227
St. Louis, MO, International Airport	62	1	97	147	170	193	227	344
		0.5	66	90	105	126	144	269
		0	31	53	68	97	104	194
Topeka, KS	61	1	102	153	192	234	245	291
		0.5	64	92	110	132	139	185
		0	23	39	52	68	84	167
Wichita, KS	60	1	115	163	209	248	285	326
		0.5	71	96	116	137	153	168
		0	24	45	57	75	83	158

[a]Heat fluxes are at the snow-melting surface only. See text for calculation of back and edge heat loss fluxes.　　　　[b]Multiply values by 0.2931 to convert to W/ft^2.

Weather Data and Heat Flux Calculation Results

Table 1 shows frequencies of snow-melting loads for 46 cities in the United States (Ramsey et al. 1999). For the calculations, the temperature of the surface of the snow-melting slab was taken to be 33°F. Any time the ambient temperature was below 32°F and it was not snowing, it was assumed that the system was idling (i.e., that heat was supplied to the slab so that melting would start immediately when snow began to fall).

Weather data were taken for the years 1982 through 1993. These years were selected because of their completeness of data. The weather data included hourly values of the precipitation amount in equivalent depth of liquid water, precipitation type, ambient dry-bulb and dew-point temperatures, wind speed, and sky cover. All weather elements for 1982 to 1990 were obtained from the *Solar and Meteorological Surface Observation Network 1961 to 1990* (*SAMSON*), *Version 1.0* (NCDC 1993). For 1991 to 1993, all weather elements except precipitation were taken from *DATSAV2* data obtained from the National Climatic Data Center as described in Colliver et al. (1998). The precipitation data for these years were taken from NCDC's *Hourly Cooperative Dataset* (NCDC 1990).

All wind speeds used were taken directly from the weather data. Wind speed V_{met} is usually measured at height of approximately 33 ft. As indicated in the section on Heat Balance, the heat and mass transfer coefficients are functions of a characteristic dimension of the snow-melting slab. The dimension used in generating the values of Table 1 was 20 ft. Sensitivity of the load to both wind speed and the characteristic dimension is included in Table 2. During snowfall, the sky temperature was taken as equal to the ambient temperature.

The first data column in Table 1 presents the average number of snowfall hours per year for each location. All surface heat fluxes were computed for snow-free area ratios of 1, 0.5, and 0, and the frequencies of snow-melting loads are presented. The frequency indicates the percentage of time that the required snow-melting surface heat flux does not exceed the value in the table for that ratio.

This table is used to design a snow-melting system for a given level of customer satisfaction depending on criticality of function. For example, although a heliport at the rooftop of a hospital may require almost 100% satisfactory operation at a snow-free ratio of 1, a residential driveway may be considered satisfactory at 90% and $A_r = 0.5$ design conditions. To optimize cost, different percentiles may be applied to different sections of the slab. For example, train station slab embark/disembark areas may be designed for a higher percentile and A_r than other sections.

Figures 1 and 2 show the distribution in the United States of snow-melting surface heat fluxes for snow-free area ratios of 1.0 and 0, respectively. The values presented satisfy the loads 99% of the time (as listed in the 99% column of Table 1). Local values can be approximated by interpolating between values given on the figure; however, extreme care must be taken because special local climatological conditions exist for many areas (e.g., lake effect snow). Both altitude and geography should be considered in making interpolations. Generally, locations in the northern plains of the United States require the maximum snow-melting heat flux (Chapman 1999).

Example for Surface Heat Flux Calculation Using Table 1

Example 2. Consider the design of a system for Albany, New York, which has an installed heat flux capacity at the top surface of approximately 149 Btu/h·ft². Based on data in Table 1, this system will keep the surface completely free of snow 95% of the time. Because there are 156 snowfall hours in an average year, this design would have some accumulation of snow approximately 8 h per year (the remaining 5% of the 156 h). This design will also meet the load for more than 98% of the time (i.e., more than 153 of the 156 snowfall hours) at an area ratio of 0.5 and more than 99% of the time for an area ratio of 0. $A_r = 0.5$ means that there is a thin layer of snow over all or part of the slab such that it acts as though half the slab is insulated by a snow layer; $A_r = 0$ means

that the snow layer is sufficient to insulate the surface from heat and evaporation losses, but that snow is melting at the base of this layer at the same rate that it is falling on the top of the layer.

Therefore, the results for this system can be interpreted to mean the following (all times are rounded to the nearest hour):

(a) For all but 8 h of the year, the slab will be snow-free.
(b) For the less than 5 h between the 95% and 98% nonexceedance values, there will be a thin build-up of snow on part of the slab.
(c) For the less than 2 h between the 98% and 99% nonexceedance values, snow will accumulate on the slab to a thickness at which the snow blanket insulates the slab, but the thickness will not increase beyond that level.
(d) For less than 2 h, the system can not keep up with the snowfall.

An examination of the 100% column shows that to keep up with the snowfall the last 1% of the time, in this case less than 2 h for an average year, would require a system capacity of approximately 276 Btu/h·ft²; to attempt to keep the slab completely snow-free the entire season requires a capacity of 321 Btu/h·ft². Based on this interpretation, the designer and customer must decide the acceptable operating conditions. Note that the heat flux values in this example do not include back or edge losses, which must be added in sizing energy source and heat delivery systems.

Sensitivity of Design Surface Heat Flux to Wind Speed and Surface Size

Some snow-melting systems are in sheltered areas, whereas others may be in locations where surroundings create a wind tunnel effect. Similarly, systems vary in size from the baseline characteristic length of 20 ft. For example, sidewalks exposed to a crosswind may have a characteristic length on the order of 5 ft. In such cases, the wind speed will be either less than or greater than the meteorological value V_{met} used in Table 1. To establish the sensitivity of the surface heat flux to wind speed and characteristic length, calculations were performed at combinations of wind speeds $0.5V_{met}$, V_{met}, and $2V_{met}$ and L values of 5 ft and 20 ft for area ratios A_r of 1.0 and 0.5. Wind speed and system size do not affect the load values for $A_r = 0$ because the calculations assume that no heat or mass transfer from the surface occurs at this condition. Table 2 presents a set of mean values of multipliers that can be applied to the loads presented in Table 1; these multipliers were established by examining the effect on the 99% nonexceedance values. The ratio of V to V_{met} in a given design problem may be determined from information given in Chapter 15 of the 2005 *ASHRAE Handbook—Fundamentals*. The closest ratio in Table 2 can then be selected. The designer is cautioned that these are to be used only as guidelines on the effect of wind speed and size variations.

Back and Edge Heat Losses

The surface heat fluxes in Table 1 do not account for heat losses from the back and edges of the slab. Adlam (1950) demonstrated that these back and edge losses may vary from 4 to 50%, depending on factors such as slab construction, operating temperature, ground temperature, and back and edge insulation and exposure. With the construction shown in Figure 3 or Figure 5 and ground temperature of 40°F at a depth of 24 in., back losses are approximately 20%. Higher losses occur with (1) colder ground, (2) more cover over the slab, or (3) exposed back, such as on bridges or parking decks.

Transient Analysis of System Performance

Determination of snow-melting surface heat fluxes as described in Equations (1) to (14) is based on steady-state analysis. Snow-melting systems generally have heating elements embedded in material of significant thermal mass. Transient effects, such as occur when the system is started, may be significant. A transient analysis method was developed by Spitler et al. (2002) and showed that particular storm conditions could change the snow-melting surface heat flux requirement significantly, depending on the precipitation rate at a particular time in the storm. It is therefore difficult to
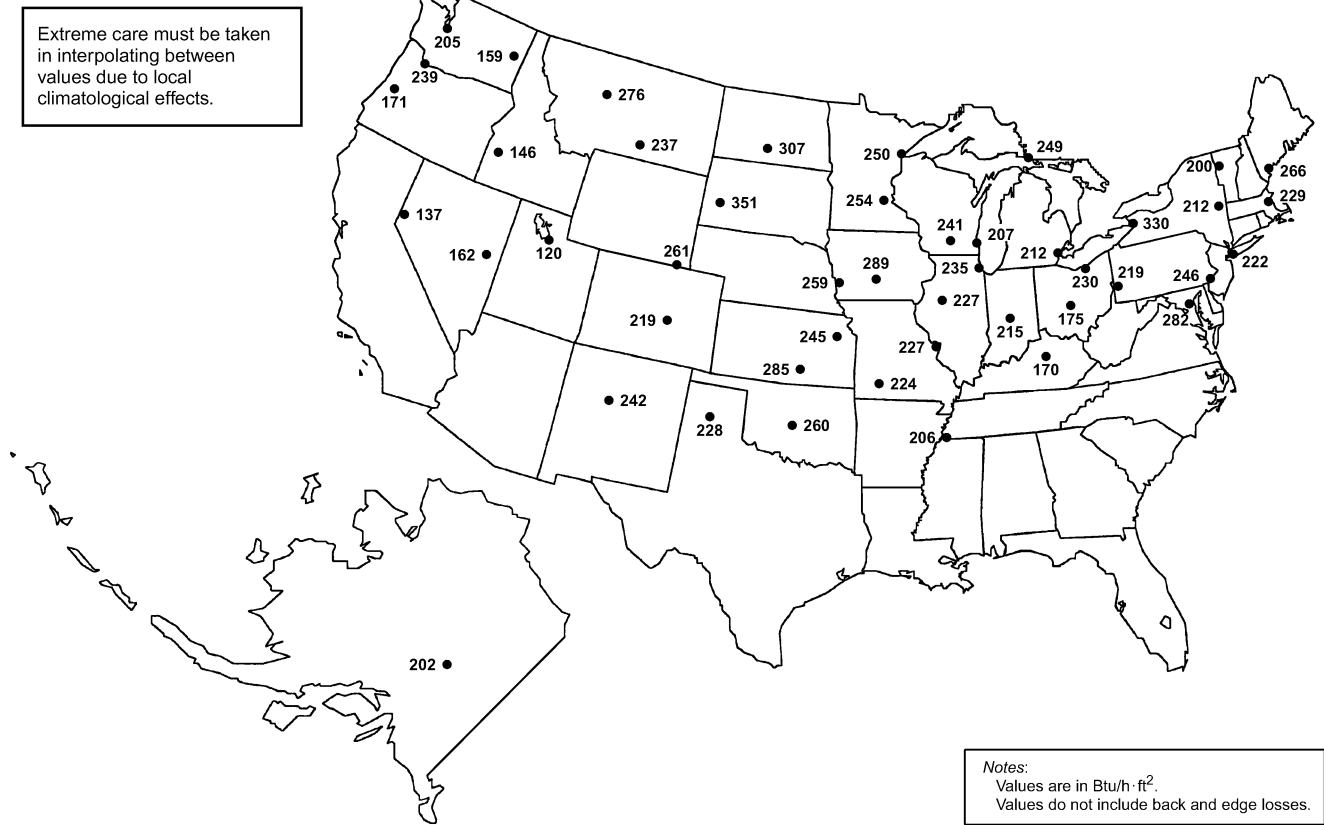
Fig. 1   Snow-Melting Surface Heat Fluxes Required to Provide Snow-Free Area Ratio of 1.0 for 99% of Time
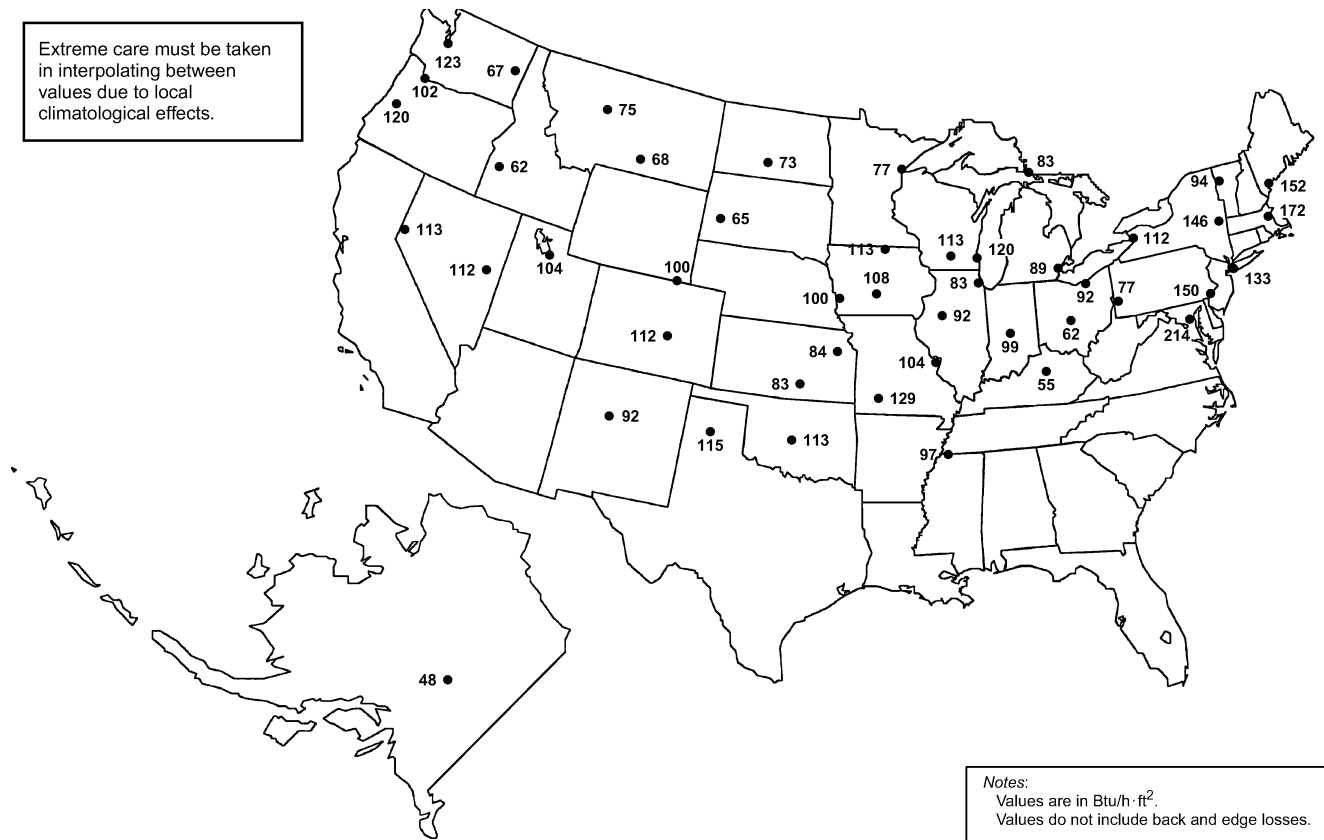
Fig. 2   Snow-Melting Surface Heat Fluxes Required to Provide Snow-Free Area Ratio of 0 for 99% of Time

Table 2 Mean Sensitivity of Snow-Melting Surface Heat Fluxes to Wind Speed and Slab Length

For loads not exceeded during 99% of snowfall hours, 1982 through 1993

Snow-Free Area Ratio, A_r	Ratio of Flux at Stated Condition to Flux at $L = 20$ ft and $V = V_{met}$				
	$L = 20$ ft		$L = 5$ ft		
	$V = 0.5V_{met}$	$V = 2V_{met}$	$V = V_{met}$	$V = 0.5V_{met}$	$V = 2V_{met}$
1	0.7	1.6	1.2	0.8	2.0
0.5	0.8	1.4	1.2	0.9	1.7
0	1.0	1.0	1.0	1.0	1.0

Note: Based on data from U.S. locations.
L = characteristic length
V_{met} = meteorological wind speed from NCDC

find simple general design rules that account for transient effects. To keep slab surfaces clear from snow during the first hour of the snowstorm, when the system is just starting to operate, heat fluxes up to five times greater than those indicated by steady-state analysis could be required. In general, greater heat input is required for greater spacing and greater depth of the heating elements in the slab; however, because of transient effects, this is not always true.

Transient analysis (Spitler et al. 2002) has also been used to examine back and edge losses. Heat fluxes because of back losses in systems without insulation ranged from 10 to 30% of the surface heat flux, depending primarily on the particular storm data, though higher losses occurred where heating elements were embedded deeper in the slab. In cases where 2 in. of insulation was applied below the slab, back losses were significantly reduced, to 1 to 4%. Although peak losses were reduced, the surface heat fluxes required to melt the snow were not significantly affected by the presence of insulation, because transient effects at the start of system operation drive the peak design surface heat fluxes. Edge losses ranged from 15 to 35% of the heat delivered by the heating element nearest the edge. This may be converted to an approximately equivalent surface heat flux percentage by reducing the snow-melting surface length and width by an amount equal to two-thirds of the heating element spacing in the slab. Then the design surface heat flux may be adjusted by the ratio of the actual snow-melting surface area to the reduced surface area as described here. The effect of edge insulation was found to be similar to that at the back of the slab. Although edge insulation does not reduce the surface heat flux requirement significantly, increased snow accumulation at the edges should be expected.

Annual Operating Data

Annual operating data for the cities in Table 1 are presented in Table 3. Melting and idling hours are summarized in this table along with the energy per unit area needed to operate the system during an average year based on calculations for the years 1982 to 1993. Back and edge heat losses are not included in the energy values in Table 3. Data are presented for snow-free area ratios of 1.0, 0.5, and 0.

The energy per unit area values are based on systems designed to satisfy the loads 99% of the time (i.e., at the levels indicated in the 99% column in Table 1) for each A_r value. The energy use for each melting hour is taken as either (1) the actual energy required to maintain the surface at 33°F or (2) the design output, whichever is less. The design snow-melting energy differs, of course, depending on whether the design is for $A_r = 1.0$, 0.5, or 0; therefore, the annual melting energy differs as well.

The idling hours include all non-snowfall hours when the ambient temperature is below 32°F. The energy consumption for each idling hour is based on either (1) the actual energy required to maintain the surface at 32°F or (2) the design snow-melting energy, whichever is less.

In Table 3, the column labeled "2% Min. Snow Temp." is the temperature below which only 2% of the snowfall hours occur. This table may only be used to predict annual operating costs. Use Table 1 for system sizing.

Annual Operating Cost Example

Example 3. A snow-melting system of 2000 ft² is to be installed in Chicago. The application is considered critical enough that the system is designed to remain snow-free 99% of the time. Table 3 shows that the annual energy requirement to melt the snow is 8501 Btu/ft². Assuming a fossil fuel cost of $8 per 10⁶ Btu, an electric cost of $0.07 per kWh, and back loss at 30%, find and compare the annual cost to melt snow with hydronic and electric systems. For the hydronic system, boiler combustion efficiency is 0.85 and energy distribution efficiency is 0.90.

Solution: Operating cost O may be expressed as follows:

$$O = \frac{A_t Q_a F}{[1 - (B/100)](\eta_b \eta_d)} \tag{15}$$

where
 O = annual operating cost $/yr
 A_t = total snow-melting area, ft²
 Q_a = annual snow-melting or idling energy requirement, Btu/ft² or kWh/ft²
 F = primary energy cost $/Btu or $/kWh
 B = back heat loss percentage, %
 η_b = combustion efficiency of boiler (or COP of a heat pump in heating mode), dimensionless. If a waste energy source is directly used for snow-melting or idling purposes, the combustion efficiency term is neglected.
 η_d = energy distribution efficiency, dimensionless (in an electric system, efficiencies may be taken to be 1)

Operating cost for a hydronic system is

$$O = \frac{(2000)(8501)(8 \times 10^{-6})}{\left[1 - \left(\frac{30}{100}\right)\right][(0.85)(0.90)]} = \$254/yr$$

Operating cost for an electric system is

$$O = \frac{[2000(8501 \times 0.2931 \times 10^{-3})(0.07)]}{1 - (30/100)} = \$498/yr$$

It is desirable to use waste or alternative energy resources to minimize operating costs. If available in large quantities, low-temperature energy resources may replace primary energy resources, because the temperature requirement is generally moderate (Kilkis 1995). Heat pipes may also be used to exploit ground heat (Shirakawa et al. 1985).

SLAB DESIGN

Either concrete or asphalt slabs may be used for snow-melting systems. The thermal conductivity of asphalt is less than that of concrete; pipe or electric cable spacing and required fluid temperatures are thus different. Hot asphalt may damage plastic or electric (except mineral-insulated cable) snow-melting systems unless adequate precautions are taken. For specific recommendations, see the sections on Hydronic System Design and Electric System Design.

Concrete slabs containing hydronic or electric snow-melting apparatus must have a subbase, expansion-contraction joints, reinforcement, and drainage to prevent slab cracking; otherwise, crack-induced shearing or tensile forces could break the pipe or cable. The pipe or cable must not run through expansion-contraction joints, keyed construction joints, or control joints (dummy grooves); however, the pipe or cable may be run under 0.12 in. score marks or saw cuts (block and other patterns). Sleeved pipe is allowed to cross expansion joints (see Figure 4). Control joints must be placed wherever the slab changes size or incline. The maximum distance between control joints for ground-supported slabs should be less than 15 ft, and the length should be no greater than twice the width,

Table 3   Annual Operating Data at 99% Satisfaction Level of Heat Flux Requirement

| | | | 2% Min. Snow Temp., °F | Annual Energy Requirement per Unit Area at Steady-State Conditions,[a] Btu/ft^2 [b] | | | | | |
| City | Time, h/yr | | | System Designed for $A_r = 1$ | | System Designed for $A_r = 0.5$ | | System Designed for $A_r = 0$ | |
	Melting	Idling		Melting	Idling	Melting	Idling	Melting	Idling
Albany, NY	156	1,883	9.3	10,132	109,230	7,252	109,004	4,371	108,420
Albuquerque, NM	44	954	16.3	2,455	38,504	1,729	38,495	984	38,332
Amarillo, TX	64	1,212	6.8	5,276	62,557	3,314	62,136	1,357	61,170
Billings, MT	225	1,800	−10.8	17,299	116,947	10,526	111,803	3,716	91,360
Bismarck, ND	158	2,887	−8.8	16,295	207,888	9,321	201,565	2,300	157,503
Boise, ID	85	1,611	5.3	3,543	74,724	2,449	73,015	1,345	68,456
Boston, MA	112	1,273	16.3	7,694	77,992	5,455	77,907	3,218	77,747
Buffalo, NY	292	1,779	3.8	23,929	105,839	14,735	105,521	5,563	101,945
Burlington, VT	204	2,215	4.3	13,182	147,122	8,485	143,824	3,783	134,634
Cheyenne, WY	224	2,152	−15.8	20,061	126,714	11,931	125,635	3,782	120,915
Chicago, IL, O'Hare International Airport	124	1,854	3.8	8,501	116,663	5,402	112,763	2,252	100,427
Cleveland, OH	188	1,570	8.8	11,419	86,539	7,359	85,470	3,208	80,851
Colorado Springs, CO	159	1,925	−8.8	11,137	97,060	7,089	96,847	3,026	96,244
Columbus, OH, International Airport	92	1,429	12.8	4,581	71,037	2,972	68,002	1,367	62,038
Des Moines, IA	127	1,954	−1.8	10,884	128,140	6,796	125,931	2,654	116,545
Detroit, MI, Metro Airport	153	1,781	11.3	10,199	104,404	6,467	102,289	2,704	95,777
Duluth, MN	238	3,206	0.3	20,838	251,218	12,423	236,657	3,969	187,820
Ely, NV	153	2,445	13.3	7,421	141,288	5,268	139,242	3,098	136,920
Eugene, OR	18	481	15.8	841	17,018	634	16,997	429	16,992
Fairbanks, AK	288	4,258	−15.8	19,803	343,674	11,700	318,880	3,559	194,237
Baltimore, MD, BWI Airport	56	957	16.3	3,827	45,132	2,970	45,132	2,121	45,130
Great Falls, MT	233	1,907	−15.8	19,703	123,801	11,731	120,603	3,736	101,712
Indianapolis, IN	96	1,473	10.8	6,558	80,942	4,132	78,532	1,705	75,926
Lexington, KY	50	1,106	13.3	2,696	54,084	1,718	52,278	733	45,859
Madison, WI	161	2,308	5.3	11,404	149,363	7,279	147,112	3,094	140,108
Memphis, TN	13	473	12.8	1,010	21,756	691	21,518	373	21,102
Milwaukee, WI	161	1,960	7.3	11,678	127,230	7,564	123,960	3,431	119,945
Minneapolis-St. Paul, MN	199	2,513	0.3	16,532	183,980	10,325	178,495	4,097	166,921
New York, NY, JFK Airport	61	885	18.3	4,193	50,680	2,988	50,467	1,797	50,049
Oklahoma City, OK	35	686	6.8	2,955	40,957	1,850	39,725	741	38,308
Omaha, NE	94	1,981	−2.3	7,425	124,274	4,613	119,565	1,790	112,700
Peoria, IL	91	1,748	2.3	6,544	104,380	4,078	100,581	1,606	94,045
Philadelphia, PA, International Airport	56	992	18.3	3,758	50,494	2,669	50,412	1,588	50,203
Pittsburgh, PA, International Airport	168	1,514	9.3	10,029	79,312	6,350	77,750	2,626	72,361
Portland, ME	157	1,996	7.3	13,318	115,248	8,969	115,196	4,630	114,836
Portland, OR	15	329	21.8	623	13,399	464	13,194	310	12,918
Rapid City, SD	177	2,154	−4.8	16,889	137,523	9,738	135,024	2,535	106,102
Reno, NV	63	1,436	16.3	2,293	54,713	1,792	54,706	1,302	54,703
Salt Lake City, UT	142	1,578	16.3	5,263	70,254	4,271	69,927	3,286	69,927
Sault Ste. Marie, MI	425	2,731	−0.3	34,249	176,517	20,779	174,506	7,250	155,508
Seattle, WA	27	260	17.8	1,212	10,482	943	10,473	682	10,452
Spokane, WA	144	1,832	10.8	6,909	81,000	4,721	79,177	2,512	75,659
Springfield, MO	58	1,108	6.8	4,401	57,165	2,950	56,929	1,503	56,238
St. Louis, MO, International Airport	62	1,150	6.8	4,516	64,668	2,981	63,428	1,446	60,764
Topeka, KS	61	1,409	−1.8	4,507	75,598	2,821	74,028	1,126	68,402
Wichita, KS	60	1,223	0.3	4,961	69,187	3,106	67,828	1,229	60,991

[a]Does not include back and edge heat losses. [b]Multiply values listed by 2.93 × 10^{-4} to convert to kWh/ft^2.

except for ribbon driveways or sidewalks. In ground-supported slabs, most cracking occurs during the early cure. Depending on the amount of water used in the concrete mix, shrinkage during cure may be up to 0.75 in. per 100 ft. If the slab is more than 15 ft long, the concrete does not have sufficient strength to overcome friction between it and the ground while shrinking during the cure period.

If the slabs are poured in two separate layers, the top layer, which contains the snow-melting apparatus, usually does not contribute toward total slab strength; therefore, the lower layer must be designed to provide the total strength.

The concrete mix of the top layer should give maximum weatherability. The compressive strength should be 4000 to 5000 psi; recommended slump is 3 in. maximum, 2 in. minimum. Aggregate size and air content should be as follows:

Table 4   Required Aggregate Size and Air Content

Maximum Size Crushed Rock Aggregate, in.	Air Content, %
2.5	5 ± 1
1	6 ± 1
0.5	7.5 ± 1

Source: Potter (1967).   *Note*: Do not use river gravel or slag.

The pipe or cable may be placed in contact with an existing sound slab (either concrete or asphalt) and then covered as described in the sections on Hydronic System Design and Electric System Design. If there are signs of cracking or heaving, the slab should be replaced. Pipe or cable should not be placed over existing expansion-contraction, control, or construction joints. The finest grade of asphalt is best for the top course; stone diameter should not exceed 0.38 in.

A moisture barrier should be placed between any insulation and the fill. If insulation is used, it should be nonhygroscopic. The joints in the barrier should be sealed and the fill made smooth enough to eliminate holes or gaps for moisture transfer. Also, the edges of the barrier should be flashed to the surface of the slab to seal the ends.

Snow-melting systems should have good surface drainage. When the ambient air temperature is 32°F or below, runoff from melting snow freezes immediately after leaving the heated area. Any water that gets under the slab also freezes when the system is shutdown, causing extreme frost heaving. Runoff should be piped away in drains that are heated or below the frost line. If the snow-melting surface is inclined (e.g., a ramp), surface runoff may collect at the lowest point. In addition to effective drainage down the ramp, the adjacent area may require heating to prevent freezing the accumulated runoff.

The area to be protected by the snow-melting system must first be measured and planned. For total snow removal, hydronic or electric heat must cover the entire area. In larger installations, it may be desirable to melt snow and ice from only the most frequently used areas, such as walkways and wheel tracks for trucks and autos. Planning for separate circuits should be considered so that areas within the system can be heated individually, as required.

Where snow-melting apparatus must be run around obstacles (e.g., a storm sewer grate), the pipe or cable spacing should be uniformly reduced. Because some drifting will occur adjacent to walls or vertical surfaces, extra heating capacity should be provided in these areas, and if possible also in the vertical surface. Drainage flowing through the area expected to be drifted tends to wash away some snow.

CONTROL

Manual Control

Manual operation is strictly by on-off control; an operator must activate and deactivate the system when snow falls. The system should be started at an idling load before snowfall, when-

ever possible, to minimize thermal stresses in the system and the slab. The system must continue to operate until all the snow on the slab melts and evaporates.

Automatic Control

If the snow-melting system is not turned on until snow starts falling, it may not melt snow effectively for several hours, giving additional snowfall a chance to accumulate and increasing the time needed to melt the area. Automatic controls provide satisfactory operation by activating the system when light snow starts, allowing adequate warm-up before heavy snowfall develops. Automatic deactivation reduces operating costs.

Snow Detectors. Snow detectors monitor precipitation and temperature. They allow operation only when snow is present and may incorporate a delay-off timer. Snow detectors located in the heated area activate the snow-melting system when precipitation (snow) occurs at a temperature below the preset slab temperature (usually 40°F). Another type of snow detector is mounted above ground, adjacent to the heated area, without cutting into the existing system; however, it does not detect tracked or drifting snow. Both types of sensors should be located so that they are not affected by overhangs, trees, blown snow, or other local conditions.

Slab Temperature Sensor. To limit energy waste during normal and light snow conditions, it is common to include a remote temperature sensor installed midway between two pipes or cables in the slab; the set point is adjusted between 40 and 60°F. Thus, during mild weather snow conditions, the system is automatically modulated or cycled on and off to keep the slab temperature (at the sensor) at set point.

Outdoor Thermostat. The control system may include an outdoor thermostat that deactivates the system when the outdoor ambient temperature rises above 35 to 40°F as automatic protection against accidental operation in summer or mild weather.

Control Selection

For optimum operating convenience and minimum operating cost, all of the previously mentioned controls should be incorporated in the snow-melting system.

Operating Cost

To evaluate operating cost during idling or melting, use the annual output data from Table 3. Idling and melting data are based on slab surface temperature control at 32°F during idling, which requires a slab temperature sensor. Without a slab temperature sensor, operating costs will be substantially higher.

HYDRONIC SYSTEM DESIGN

Hydronic system design includes selection of the following components: (1) heat transfer fluid, (2) piping, (3) fluid heater, (4) pump(s) to circulate the fluid, and (5) controls. With concrete slabs, thermal stress is also a design consideration.

Heat Transfer Fluid

Various fluids, including brine, oils, and glycol-water, are suitable for transferring heat from the fluid heater to the slab. Freeze protection is essential because most systems will not be operated continuously in subfreezing weather. Without freeze protection, power loss or pump failure could cause freeze damage to the piping and slab.

Brine is the least costly heat transfer fluid, but it has a lower specific heat than glycol. Using brine may be discouraged because of the cost of heating equipment that resists its corrosive potential.

Although **heat transfer oils** are not corrosive, they are more expensive than brine or glycol and have a lower specific heat and higher viscosity. Petroleum distillates used in snow-melting systems are classified as nonflammable but have fire points between

300 and 350°F. When oils are used as heat transfer fluids, any oil dripping from pump seals should be collected. It is good practice to place a barrier between the oil lines and the boiler so that a flashback from the boiler cannot ignite a possible oil leak. Other nonflammable fluids, such as those used in some transformers, can be used as antifreeze.

Glycols (ethylene glycol and propylene glycol) are the most popular in snow-melting systems because of their moderate cost, high specific heat, and low viscosity; ease of corrosion control is another advantage. Automotive glycols containing silicates are not recommended because they can cause fouling, pump seal wear, fluid gelation, and reduced heat transfer. The piping should be designed for periodic addition of an inhibitor. Glycols should be tested annually to determine any change in reserve alkalinity and freeze protection. Only inhibitors obtained from the manufacturer of the glycol should be added. Heat exchanger surfaces should be kept below 285°F, which corresponds to about 40 psig steam. Temperatures above 300°F accelerate deterioration of the inhibitors.

Because ethylene glycol and petroleum distillates are toxic, no permanent connection should be installed between the snow-melting system and the drinking water supply. Gordon (1950) discusses precautions concerning internal corrosion, flammability, toxicity, cleaning, joints, and hook-up that should be taken during installation of hydronic piping. The properties of brine and glycol are discussed in Chapter 21 of the 2005 *ASHRAE Handbook—Fundamentals*. The effect of glycol on system performance is detailed in Chapter 12 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*.

Piping

Piping may be metal, plastic, or ethylene-propylene terpolymer (EPDM). Steel, iron, and copper pipes have long been used, but steel and iron may corrode rapidly if the pipe is not shielded by a coating and/or cathodic protection. Both the use of salts for deicing and elevated temperature accelerate corrosion of metallic components. NACE (1978) states that the corrosion rate roughly doubles for each 18°F rise in temperature.

Chapman (1952) derived the equation for the fluid temperature required to provide an output q_o. For construction as shown in Figure 3, the equation is

$$t_m = 0.5q_o + t_f \qquad (16)$$

where t_m = average fluid (antifreeze solution) temperature, °F. Equation (16) applies to 1 in. as well as 3/4 in. IPS pipe (Figure 3).

Design information about heated slabs given in Chapter 6 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment* may be used for all other types of slab construction, pipe spacing, and pipe material. In using these design equations, snow cover or water film on the slab may be treated as surface covers.

For specific conditions or for cities other than those given in Table 1, Equations (1) and (16) are used. Table 5 gives solutions to these equations at a relative humidity of 80%. Splitting the surface heat flux among four components as in Equation (1) also affects the required water temperature; therefore, Equation (16) and Table 5 should be used with caution. Table 5 may also be used to determine successful systems operation conditions. For example, if a system as shown in Figure 3 is designed for 250 Btu/h·ft², it will satisfy eight severe snow conditions such as 10°F, 0.16 in./h, and 10 mph wind speed (Chapman 1999).

Satisfactory standard practices is to use 3/4 in. pipe or tube on 12 in. centers, unless the snow-melting surface heat flux is too high. If pumping loads require reduced friction, the pipe size can be increased to 1 in., but slab thickness must be increased accordingly. Piping should be supported by a minimum of 2 in. of concrete above and below. This requires a 5 in. slab for 3/4 in. pipe and a 5.4 in. slab for 1 in. pipe.
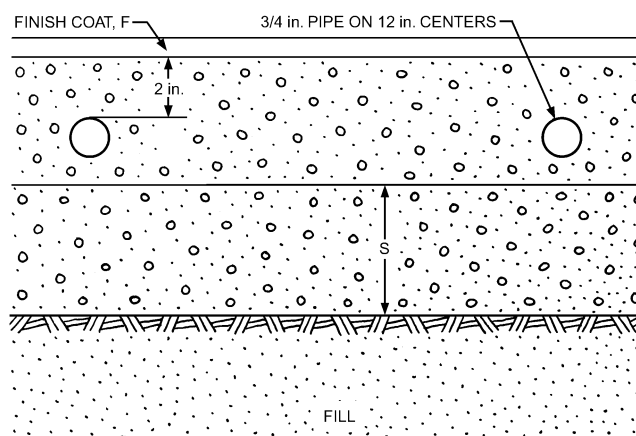
F = depth of finish coat—assumed to be 0.5 in. of concrete. Finish coat may be asphalt, but then cover slab should be reduced from 3 in. Depth of slab should always keep thermal resistance equal to 3 in. of concrete.

S = depth required by structural design (should be at least 2 in. of concrete).

Fig. 3   Detail of Typical Hydronic Snow-Melting System

Plastic Pipe. Plastic [polyethylene (PE), cross-linked polyethylene (PEX)], or multilayer pipe such as PEX-AL-PEX (a PEX inner and outer layer with a middle layer of aluminum) is popular because of lower material cost, lower installation cost, and corrosion resistance. Considerations when using plastic pipe include stress crack resistance, temperature limitations, and thermal conductivity. Heat transfer oils should not be used with plastic pipe.

Plastic pipe is furnished in coils. Smaller pipe can be bent to form a variety of heating panel designs without elbows or joints. Mechanical compression connections can be used to connect heating panel pipe to the larger supply and return piping leading to the pump and fluid heater. PE pipe may be fused using appropriate fittings and fusion equipment. Fusion joining eliminates metallic components and thus the possibility of corrosion in the piping; however, it requires considerable installation training.

When plastic pipe is used, the system must be designed so that the fluid temperature required will not damage the pipe. If a design requires a temperature above the tolerance of plastic pipe, the delivered heat flux will never meet design requirements. The PE temperature limit is typically 140°F. For PEX, the temperature is 200°F (up to 80 psi) sustained fluid temperature, or 180°F (up to 100 psi). A solution to temperature limitations is to decrease the pipe spacing. Closer pipe spacing also helps eliminate striping of snow (unmelted portions between adjacent pipe projections on the surface). Adlam (1950) addresses the parameter of pipe size and the effect of pipe spacing on heat output. A typical solution is summarized in Table 6, which shows a way of designing pipe spacing according to flux requirements. This table also shows adjustments for the effect of more than 2 in. of concrete or paver over the pipe.

Oxygen permeation through plastic pipes may lead to corrosion on metal surfaces in the entire system unless plastic pipes are equipped with an oxygen barrier layer. Otherwise, either a heat exchanger must separate the plastic pipe circuitry from the rest of the system or corrosion-inhibiting additives must be used in the entire hydronic system.

Pipe Installation. It is good design practice to avoid passing any embedded piping through a concrete expansion joint; otherwise, the pipe may be stressed and possibly ruptured. Figure 4 shows a method of protecting piping that must pass through a concrete expansion joint from stress under normal conditions.

After pipe installation, but before slab installation, all piping should be air-tested to about 100 psig. This pressure should be maintained until all welds and connections have been checked for

Table 5   Steady-State Surface Heat Fluxes and Average Fluid Temperature for Hydronic Snow-Melting System in Figure 3

(Average fluid temperature based on 12 in. tube spacing)

s, Rate of Snowfall in/h	A_r		$t_a = 0°F$ Wind Speed V, mph			$t_a = 10°F$ Wind Speed V, mph			$t_a = 20°F$ Wind Speed V, mph			$t_a = 30°F$ Wind Speed V, mph		
			5	10	15	5	10	15	5	10	15	5	10	15
0.08	1.0	q_o	166	222	272	138	180	217	108	135	159	76	86	94
		t_m	116	144	169	102	123	142	87	100	112	71	76	80
	0.0	q_o	67	67	67	65	65	65	63	63	63	61	61	61
		t_m	66	66	66	65	65	65	64	64	64	63	63	63
0.16	1.0	q_o	233	289	339	203	244	282	171	197	221	136	146	155
		t_m	149	177	202	134	155	174	118	132	144	101	106	110
	0.0	q_o	133	133	133	129	129	129	125	125	125	121	121	121
		t_m	100	100	100	98	98	98	96	96	96	93	93	93
0.25	1.0	q_o	308	363	414	275	317	354	241	268	292	204	214	223
		t_m	187	215	240	171	192	210	154	167	179	135	140	144
	0.0	q_o	208	208	208	202	202	202	195	195	195	189	189	189
		t_m	137	137	137	134	134	134	131	131	131	127	127	127

Note: Table based on a characteristic slab length of 20 ft, standard air pressure, a water film temperature of 33°F, and relative humidity of 80%.

A_r = snow-free area ratio t_a = atmospheric dry-bulb temperature, °F
q_o = slab heating flux, Btu/h·ft² t_m = average fluid temperature based on construction shown in Figure 3, °F

Table 6   Typical Dependency of Maximum Heat Flux Deliverable by Plastic Pipes on Pipe Spacing and Concrete Overpour

(Average fluid temperature = 130°F)

Heat Flux,[a] Btu/h · ft²	Pipe Spacing on Centers,[b] in.
200	12
250	9
300	6
400	4

[a]Heat flux per unit area. Includes 30% back loss. Increase to 50% for bridges and structures with exposed back.
[b]Space pipes 1 in. closer for each 1 in. of concrete cover over 2 in. Space pipes 2 in. closer for each 1 in. of brick paver and mortar.
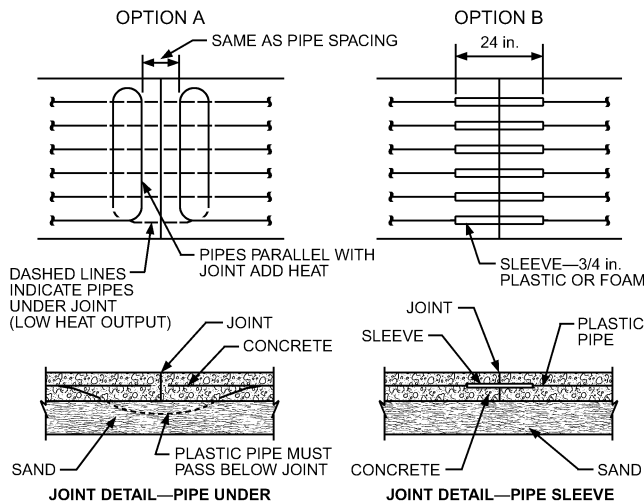
Fig. 4   Piping Details for Concrete Construction

leaks. Isolate the air pressure test to manifold and piping, because boilers or other energy-converting, accumulating, or conditioning equipment may have lower pressure test limits. For example, boilers normally have an air test capability of 30 psi. Testing should not be done with water because (1) small leaks may not be observed

during slab installation; (2) water leaks may damage the concrete during installation; (3) the system may freeze before antifreeze is added; and (4) it is difficult to add antifreeze when the system is filled with water.

Air Control. Because introducing air causes deterioration of the antifreeze, the piping should not be vented to the atmosphere. It should be divided into smaller zones to facilitate filling and allow isolation when service is necessary.

Air can be eliminated from piping during initial filling by pumping the antifreeze from an open container into isolated zones of the piping. A properly sized pump and piping system that maintains adequate fluid velocity, together with an air separator and expansion tank, will keep air from entering the system during operation.

A strainer, sediment trap, or other means for cleaning the piping system may be provided. It should be placed in the return line ahead of the heat exchanger and must be cleaned frequently during initial system operation to remove scale and sludge. A strainer should be checked and cleaned, if necessary, at the start of and periodically during each snow-melting season.

An ASME safety relief valve of adequate capacity should be installed on a closed system.

Fluid Heater

The heat transfer fluid can be heated using any of a variety of energy sources, depending on availability. A fluid heater can use steam, hot water, gas, oil, or electricity. In some applications, heat may be available from secondary sources, such as engine generators, condensate, and other waste heat sources. Other low-temperature waste, or alternative energy resources may also be used with or without heat pumps or heat pipes. In a district heating system, the snow-melting system may be tied to the return piping of the district, which increases the overall temperature drop in the district heating system (Brown 1999).

The design capacity of the fluid heater can be established by evaluating the data in the section on Snow-Melting Heat Flux Requirement; it is usually 200 to 300 Btu/h·ft², which includes back and edge losses.

Design of the fluid heater should follow standard practice, with adjustments for the film coefficient. Consideration should be given to flue gas condensation and thermal shock in boilers because of

low fluid temperatures. Bypass flow and temperature controls may be necessary to maintain recommended boiler temperatures. Boilers should be derated for high-altitude applications.

Pump Selection

The proper pump is selected based on the (1) fluid flow rate; (2) energy requirements of the piping system; (3) specific heat of the fluid; and (4) viscosity of the fluid, particularly during a cold start-up.

Pump Selection Example

Example 3. An area of 10,000 ft² is to be designed with a snow-melting system. Using the criteria of Equation (1), a heat flux (including back and edge losses) of 250 Btu/h·ft² is selected. Thus, the total fluid heater output must be 2,500,000 Btu/h, neglecting energy distribution losses. Size the pump for the heat transfer fluid used.

Solution: For a fluid with a specific heat of 0.85 Btu/lb·°F, the flow or temperature drop must be adjusted by 15%. From Equation (18) in Chapter 12 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*, for a 23°F temperature drop, flow would be 250 gpm. If glycol is used at 130°F, the effect on pipe pressure loss and pump performance is negligible. If the system head is 40 ft and pump efficiency 60%, pump horsepower is 4.2. Centrifugal pump design criteria may be found in Chapter 39 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*.

Controls

The controls discussed in the section on Control (Hydronic and Electric) provide convenience and operating economy but are not required for operation. Hydronic systems require fluid temperature control for safety and for component longevity. Slab stress and temperature limits of the heat transfer fluid, pipe components, and fluid heater need to be considered. Certain nonmetallic pipe materials should not be subjected to temperatures above 140°F. If the primary control fails, a secondary fluid temperature sensor should deactivate the snow-melting system and possibly activate an alarm.

Thermal Stress

Chapman (1955) discusses the problems of thermal stress in a concrete slab. In general, thermal stress will cause no problems if the following installation and operation rules are observed:

- Minimize the temperature difference between the fluid and the slab surface by maintaining (1) close pipe spacing (see Figure 3), (2) a low temperature differential in the fluid (less than 20°F), and (3) continuous operation (if economically feasible). According to Shirakawa et al. (1985), the temperature difference between the slab surface and the heating element skin should not exceed 70°F during operation.
- Install pipe within about 2 in. of the surface.
- Use reinforcing steel designed for thermal stress if high structural loads are expected (such as on highways).

Thermal shock to the slab may occur if heated fluid is introduced from a large source of residual heat such as a storage tank, a large piping system, or another snow-melting area. The slab should be brought up to temperature by maintaining the fluid temperature differential at less than 20°F.

ELECTRIC SYSTEM DESIGN

Snow-melting systems using electricity as an energy source have heating elements in the form of (1) mineral-insulated (MI) cable, (2) self-regulating cable, (3) constant-wattage cable, or (4) high-intensity infrared heaters.

Heat Flux

The basic load calculations for electric systems are the same as presented in the section on Snow-Melting Heat Flux Requirement.

However, because electric system output is determined by the resistance installed and the voltage impressed, it cannot be altered by fluid flow rates or temperatures. Consequently, neither safety factors nor marginal capacity systems are design considerations.

Heat flux within a slab can be varied by altering the heating cable spacing to compensate for anticipated drift areas or other high-heat-loss areas. Power density should not exceed 120 W/ft² (NFPA *Standard* 70).

Electrical Equipment

Installation and design of electric snow-melting systems is governed by Article 426 of the *National Electrical Code* (NEC, or NFPA *Standard* 70), which requires that each electric snow-melting circuit (except mineral-insulated, metal-sheathed cable embedded in a noncombustible medium) be provided with a ground fault protection device. An equipment protection device (EPD) with a trip level of 30 mA should be used to reduce the likelihood of nuisance tripping.

Double-pole, single-throw switches or tandem circuit breakers should be used to open both sides of the line. The switchgear may be in any protected, convenient location. It is also advisable to include a pilot lamp on the load side of each switch so that there is a visual indication when the system is energized.

Junction boxes located at grade level are susceptible to water ingress. Weatherproof junction boxes installed above grade should be used for terminations.

The power supply conduit is run underground, outside the slab, or in a prepared base. With concrete slab, this conduit should be installed before the reinforcing mesh.

Mineral-Insulated Cable

Mineral-insulated (MI) heating cable is a magnesium oxide (MgO)-filled, die-drawn cable with one or two copper or copper alloy conductors and a seamless copper or stainless steel alloy sheath. Copper sheath versions are usually protected from salts and other chemicals by a polyvinyl chloride (PVC) or high-density polyethylene jacket.

Cable Layout. To determine the characteristics of the MI heating cable needed for a specific area, the following must be known:

- Heated area size
- Power density required
- Voltage(s) available
- Approximate cable length needed

To find the approximate MI cable length, estimate 2 ft of cable per square foot of concrete. This corresponds to 6 in. on-center spacing. Actual cable spacing will vary between 3 and 9 in. for proper power density.

Cable spacing is dictated primarily by the heat-conducting ability of the material in which the cable is embedded. Concrete has a higher heat transmission coefficient than asphalt, permitting wider cable spacing. The following is a procedure to select the proper MI heating cable:

1. Determine total power required for each heated slab.

$$W = Aw \tag{17}$$

2. Determine total resistance.

$$R = E^2/W \tag{18}$$

3. Calculate cable resistance per foot.

$$r_1 = R/L_1 \tag{19}$$

where

W = total power needed, W
A = heated area of each heated slab, ft²
w = required power density input, W/ft²
R = total resistance of cable, Ω

E = voltage available, V
r_1 = calculated cable resistance, Ω per foot of cable
L_1 = estimated cable length, ft
L = actual cable length needed, ft
r = actual cable resistance, Ω/ft
d = cable on-center spacing, in.
I = total current per MI cable, A

Commercially available mineral-insulated heating cables have actual resistance values (if there are two conductors, the value is the total of the two resistances) ranging from 0.0016 to 0.6 Ω/ft. Manufacturing tolerances are ±10% on these values. MI cables are die-drawn, with the internal conductor drawn to size indirectly by pressures transmitted through the mineral insulation.

4. From manufacturers' literature, choose a cable with a resistance r closest to the calculated r_1. Note that r is generally listed at ambient room temperature. At the specific temperature, r may drift from the listed value. It may be necessary to make a correction as described in Chapter 6 of the 2004 *ASHRAE Handbook— HVAC Systems and Equipment*.

5. Determine the actual cable length needed to give the wattage desired.

$$L = R/r \qquad (20)$$

6. Determine cable spacing within the heated area.

$$d = 12A/L \qquad (21)$$

For optimum performance, heating cable spacing should be within the following limits: in concrete, 3 to 9 in.; in asphalt, 3 to 6 in.

Because the manufacturing tolerance on cable length is ±1%, and installation tolerances on cable spacing must be compatible with field conditions, it is usually necessary to adjust the installed cable as the end of the heating cable is rolled out. Cable spacing in the last several passes may have to be altered to give uniform heat distribution.

The installed cable within the heated areas follows a serpentine path originating from a corner of the heated area (Figure 5). As heat is conducted evenly from all sides of the heating cable, cables in a concrete slab can be run within half the spacing dimension of the perimeter of the heated area.

7. Determine the current required for the cable.

$$I = E/R, \text{ or } I = W/E \qquad (22)$$

8. Choose cold-lead cable as dictated by typical design guidelines and local electrical codes (see Table 7).

Cold-Lead Cable. Every MI heating cable is factory-fabricated with a non-heat-generating cold-lead cable attached. The cold-lead cable must be long enough to reach a dry location for termination and of sufficient wire gage to comply with local and *NEC* standards. The *NEC* requires a minimum cold-lead length of 6 in. within the junction box. MI cable junction boxes must be located such that the box remains dry and at least 3 ft of cold-lead cable is available at the end for any future service (Figure 5). Preferred junction box locations are indoors; on the side of a building, utility pole, or wall; or inside a manhole on the wall. Boxes should have a hole in the bottom to drain condensation. Outdoor boxes should be completely watertight except for the condensation drain hole. Where junction boxes are mounted below grade, the cable end seals must be coated with an epoxy to prevent moisture entry. Cable end seals should extend into the junction box far enough to allow the end seal to be removed if necessary.

Although MgO, the insulation in MI cable, is hygroscopic, the only vulnerable part of the cable is the end seal. However, should
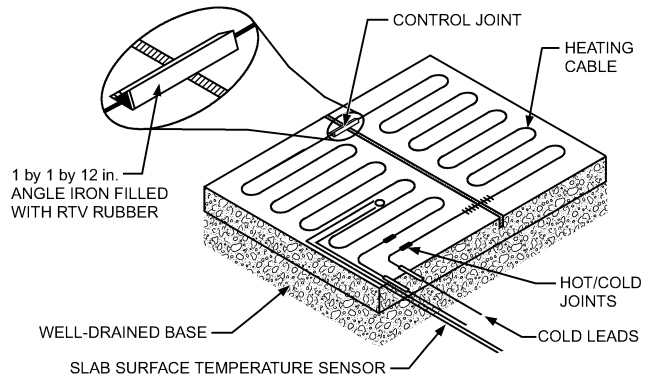
Fig. 5   Typical Mineral Insulated Heating Cable Installation in Concrete Slab

Table 7   Mineral-Insulated Cold-Lead Cables (Maximum 600 V)

Single-Conductor Cable		Two-Conductor Cable	
Current Capacity, A	American Wire Gage	Current Capacity, A	American Wire Gage
35	14	25	14/2
40	12	30	12/2
55	10	40	10/2
80	8	55	8/2
105	6	75	6/2
140	4	95	4/2
165	3		
190	2		
220	1		

Source: *National Electrical Code*® (NFPA *Standard* 70).

moisture penetrate the seal, it can easily be detected with a megohm-meter and driven out by applying a torch 2 to 3 ft from the end and working the flame toward the end.

Installation. When MI electric heating cable is installed in a concrete slab, the slab may be poured in one or two layers. In single-pour application, the cable is hooked on top of the reinforcing mesh before the pour is started. In two-layer application, the cable is laid on top of the bottom structural slab and embedded in the finish layer. For a proper bond between layers, the finish slab should be poured within 24 h of the bottom slab, and a bonding grout should be applied. The finish slab should be at least 2 in. thick. Cable should not run through expansion, control, or dummy joints (score or groove). If the cable must cross such a joint, it should cross the joint as few times as possible and be protected at the point of crossing with RTV rubber and a 1 by 1 by 12 in. angle iron as shown in Figure 5.

The cable is uncoiled from reels and laid as described in the section on Cable Layout. Prepunched copper or stainless steel spacing strips are often nailed to the lower slab for uniform spacing.

A high-density polyethylene (HDPE) or polyvinyl chloride (PVC) jacket is extruded by the manufacturer over the cable to protect from chemical damage and to protect the cable from physical damage without adding excessive thermal insulation.

If unjacketed MI cables are used, calcium chloride or other chloride additives should not be added to a concrete mix in winter because chlorides are destructive to copper. Cinder or slag fill under snow-melting slabs should also be avoided. The cold-lead cable should exit the slab underground in suitable conduits to prevent physical and chemical damage.

In asphalt slabs, the MI cable is fixed in place on top of the base pour with prepunched stainless steel strips or 6 in. by 6 in. wire mesh.
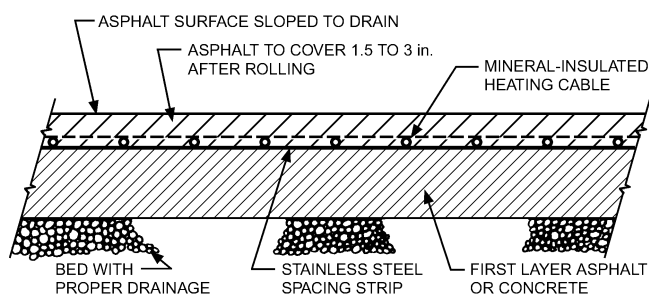
Fig. 6 Typical Section, Mineral-Insulated Heating Cable in Asphalt
(Potter 1967)

Fig. 7 Typical Self-Regulating Cable Installation

prevent them from floating when the top layer is applied. The layer of asphalt over the cable should be 1.5 to 3 in. thick (Figure 6).

Testing. Mineral-insulated heating cables should be thoroughly tested before, during, and after installation to ensure they have not been damaged either in transit or during installation.

Because MgO insulation is hygroscopic, damage to the cable sheath is easily detectable with a 500 V field megohmmeter. Cable insulation resistance should be measured on arrival of the cable. Cable with insulation resistance of less than 20 MΩ should not be used. Cable that shows a marked loss of insulation resistance after installation should be investigated for damage. Cable should also be checked for electrical continuity.

Self-Regulating Cable

Self-regulating heating cables consist of two parallel conductors embedded in a heating core made of conductive polymer. These cables automatically adjust their power output to compensate for local temperature changes. Heat is generated as electric current passes through the core between the conductors. As the slab temperature drops, the number of electrical paths increases, and more heat is produced. Conversely, as the slab temperature rises, the core has fewer electrical paths, and less heat is produced.

Power output of self-regulating cables may be specified as watts per unit length at a particular temperature or in terms of snow-melting performance at a given cable spacing. In typical slab-on-grade applications, adequate performance may be achieved with cables spaced up to 12 in. apart. Narrower cable spacings may be required to achieve the desired snow-melting performance. The parallel construction of the self-regulating cable allows it to be cut to length in the field without affecting the rated power output.

Layout. For uniform heating, the heating cable should be arranged in a serpentine pattern that covers the area with 12 in. on-center spacing (or alternative spacing determined for the design). The heating cable should not be routed closer than 4 in. to the edge of the slab, drains, anchors, or other material in the concrete.

Crossing expansion, control, or other slab joints should be avoided. Self-regulating heating cables may be crossed or overlapped as necessary. Because the cables limit power output locally, they will not burn out.

Both ends of the cable should terminate in an aboveground weatherproof junction box. Junction boxes installed at grade level are susceptible to water ingress. An allowance of heating cable should be provided at each end for termination.

The maximum circuit length published by the manufacturer for the cable type should be respected to prevent tripping of circuit breakers. Use ground fault circuit protection as required by national and local electrical codes.

Installation. Figure 7 shows a typical self-regulating cable installation. The procedure for installing a self-regulating system is as follows:
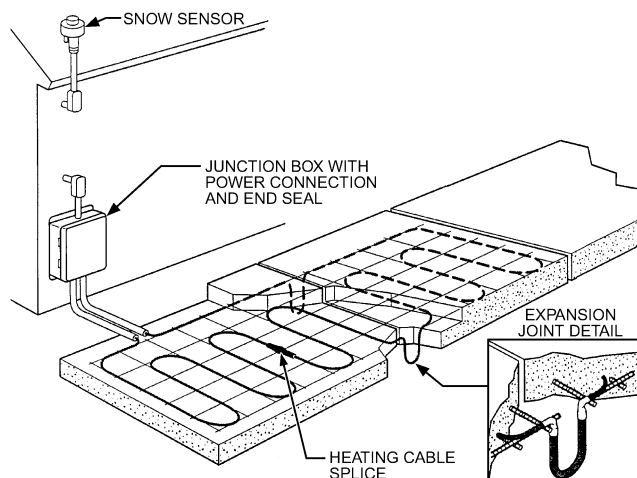
1. Hold a project coordination meeting to discuss the role of each trade and contractor. Good coordination helps ensure a successful installation.
2. Attach the heating cable to the concrete reinforcing steel or wire mesh using plastic cable ties at approximately 12 in. intervals. Reinforcing steel or wire mesh is necessary to ensure that the slab is structurally sound and that the heating cable is installed at the design depth.
3. Test the insulation resistance of the heating cable using a 2500 V dc megohmmeter connected between the braid and the two bus wires. Readings of less than 20 MΩ indicate cable jacket damage. Replace or repair damaged cable sections before the slab is poured.
4. Pour the concrete, typically in one layer. Take precautions to protect the cable during the pour. Do not strike the heating cable with sharp tools or walk on it during the pour.
5. Terminate one end of the heating cable to the power wires, and seal the other end using connection components provided by the manufacturer.

Constant-Wattage Systems

In a constant-wattage system, the resistance elements may consist of a length of copper wire or alloy with a given amount of resistance. When energized, these elements produce the required amount of heat. Witsken (1965) describes this system in further detail.

Elements are either solid-strand conductors or conductors wrapped in a spiral around a nonconducting fibrous material. Both types are covered with a layer of insulation such as PVC or silicone rubber.

The heat-generating portion of an element is the conductive core. The resistance is specified in ohms per linear foot of core. Alternately, a manufacturer may specify the wire in terms of watts per foot of core, where the power is a function of the resistance of the core, the applied voltage, and the total length of core. As with MI cable, the power output of constant-wattage cable does not change with temperature.

Considerations in the selection of insulating materials for heating elements are power density, chemical inertness, application, and end use. Polyvinyl chloride is the least expensive insulation and is widely used because it is inert to oils, hydrocarbons, and alkalies. An outer covering of nylon is often added to increase its physical strength and to protect it from abrasion. The linear power density of embedded PVC is limited to 5 W/ft. Silicone rubber is not inert to oils or hydrocarbons. It requires an additional covering—metal braid, conduit, or fiberglass braid—for protection. This material can dissipate heat of up to 10 W/ft.
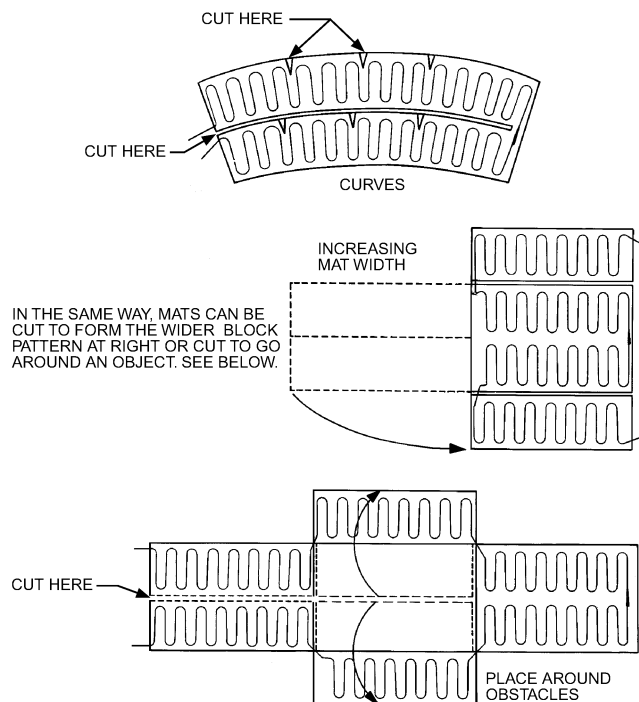
Fig. 8   Shaping Heating Mats Around Curves and Obstacles

Lead can be used to encase resistance elements insulated with glass fiber. The lead sheath is then covered with a vinyl material. Output is limited to approximately 10 W/ft by the PVC jacket.

Teflon® has good physical and electrical properties and can be used at temperatures up to 500°F.

Low-power-density (less than 10 W/ft) resistance wires may be attached to plastic or fiber mesh to form a mat unit. Prefabricated factory-assembled mats are available in a variety of watt densities for embedding in specified paving materials to match desired snow-melting capacities. Mats of lengths up to 60 ft are available for installation in asphalt sidewalks and driveways.

Preassembled heating mats of appropriate widths are also available for **stair steps**. Heating mats are seldom made larger than 60 ft^2, because larger ones are more difficult to install, both mechanically and electrically. With a series of cuts, in the plastic or fiber mesh heating mats can be tailored to follow contours of curves and fit around objects, as shown in Figure 8. Extreme care should be exercised to prevent damage to the heater wire (or lead) insulation during this operation.

Mats should be installed 1.5 to 3.0 in. below the finished surface of asphalt or concrete. Installing mats deeper decreases the snow-melting efficiency. Only mats that can withstand hot-asphalt compaction should be used for asphalt paving.

Layout. Heating wires should be long enough to fit between the concrete slab dummy groove control or construction joints. Because concrete forms may be inaccurate, 2 to 4 in. of clearance should be allowed between the edge of the concrete and the heating wire. Approximately 4 in. should be allowed between adjacent heating wires at the control or construction joints.

For asphalt, the longest wire or largest heating mat that can be used on straight runs should be selected. The mats must be placed at least 12 in. in from the slab edge. Adjacent mats must not overlap. Junction boxes should be located so that each accommodates the maximum number of mats. Wiring must conform to requirements of the *NEC* (NFPA *Standard* 70). It is best to position junction boxes adjacent to or above the slab.

Installation

General

1. Check the wire or heating mats with an ohmmeter before, during, and after installation.
2. Temporarily lay the mats in position and install conduit feeders and junction boxes. Leave enough slack in the lead wires to permit temporary removal of the mats during the first pour. Carefully ground all leads using the grounding braids provided.
3. Secure all splices with approved crimped connectors or set screw clamps. Tape all of the power splices with plastic tape to make them waterproof. All junction boxes, fittings, and snug bushings must be approved for this class of application. The entire installation must be completely waterproof to ensure trouble-free operation.

In Concrete

1. Pour and finish each slab area between the expansion joints individually. Pour the base slab and rough level to within 1.5 to 2 in. of the desired finish level. Place the mats in position and check for damage.
2. Pour the top slab over the mats while the rough slab is still wet, and cover the mats to a depth of at least 1.5 in., but not more than 2 in.
3. Do not walk on the mats or strike them with shovels or other tools.
4. Except for brief testing, do not energize the mats until the concrete is completely cured.

In Asphalt

1. Pour and level the base course. If units are to be installed on an existing asphalt surface, clean it thoroughly.
2. Apply a bituminous binder course to the lower base, install the mats, and apply a second binder coating over the mats. The finish topping over the mats should be applied in a continuous pour to a depth of 1.25 to 1.5 in. *Note*: Do not dump a large mass of hot asphalt on the mats because the heat could damage the insulation.
3. Check all circuits with an ohmmeter to be sure that no damage occurred during the installation.
4. Do not energize the system until the asphalt has completely hardened.

Infrared Snow-Melting Systems

Although overhead infrared systems can be designed specifically for snow-melting and freeze protection, they are usually installed for additional features they offer. Infrared systems provide comfort heating, which is particularly useful at entrances of plants, office buildings, and hospitals or on loading docks. Infrared lamps can improve a facility's security, safety, and appearance. These additional benefits may justify the somewhat higher cost of infrared systems.

Infrared fixtures can be installed under entrance canopies, along building facades, and on freestanding poles. Approved equipment is available for recessed, surface, and pendant mounting.

Infrared Fixture Layout. The same infrared fixtures used for comfort heating installations (as described in Chapter 15 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*) can be used for snow-melting systems. The major differences are in the orientation of the target area: whereas in comfort applications, the *vertical* surfaces of the human body constitute the target of irradiation, in snow-melting applications, a *horizontal* surface is targeted. When snow melting is the primary design concern, fixtures with narrow beam patterns confine the radiant energy within the target area for more efficient operation. Asymmetric reflector fixtures, which aim the thermal radiation primarily to one side of the fixture centerline, are often used near the periphery of the target area.

Infrared fixtures usually have a longer energy pattern parallel to the long dimension of the fixture than at right angles to it (Frier 1965). Therefore, fixtures should be mounted in a row parallel to the longest dimension of the area. If the target area is 8 ft or more in width, it is best to locate the fixtures in two or more parallel rows. This arrangement also provides better comfort heating because radiation is directed across the target area from both sides at a more favorable incident angle.

Radiation Spill. An ideal energy distribution is uniform throughout the snow-melting target area at a density equal to the design requirement. The design of heating fixture reflectors determines the percentage of the total fixture radiant output scattered outside the target area design pattern.

Even the best-controlled beam fixtures do not produce a completely sharp cutoff at the beam edges. Therefore, if uniform distribution is maintained for the full width of the area, a considerable amount of radiant energy falls outside the target area. For this reason, infrared snow-melting systems are designed so that the power density on the slab begins to decrease near the edge of the area (Frier 1964). This design procedure minimizes stray radiant energy losses.

Figure 9 shows the power densities obtained in a sample snow-melting problem (Frier 1965). The sample design average is 45 W/ft^2. It is apparent that the incident power density is above the design average value at the center of the target area and below average at the periphery. Figure 9 shows how the power density and distribution in the snow-melting area depend on the number, wattage, beam pattern, and mounting height of the heaters, and on their position relative to the slab (Frier 1964).

With distributions similar to the one in Figure 9, snow begins to collect at the edges of the area as the energy requirements for snow melting approach or exceed system capacity. As snowfall lessens, the snow at the edges of the area and possibly beyond is then melted if the system continues to operate.

Target Area Power Density. Theoretical target area power densities for snow melting with infrared systems are the same as those for commercial applications of constant-wattage systems except that back and edge heat losses are smaller. However, note that theoretical density values are for radiation incident on the slab surface, not that emitted from the lamps. Merely multiplying the recommended snow-melting power density by the slab area to obtain the total power input for the system does not result in good performance. Experience has shown that multiplying this product by a correction factor of 1.6 gives a more realistic figure for the total required power input. The resulting wattage compensates not only for the radiant inefficiency

involved, but also for the radiation falling outside the target area. For small areas, or when the fixture mounting height exceeds 16 ft, the multiplier can be as large as 2.0; large areas with sides of approximately equal length can have a multiplier of about 1.4.

The point-by-point method is the best way to calculate the fixture requirements for an installation. This method involves dividing the target area into 1 ft squares and adding the radiant energy from each infrared fixture incident on each square (Figure 9). The radiant energy distribution of a given infrared fixture can be obtained from the equipment manufacturer and should be followed for that fixture size and placement.

With infrared energy, the target area can be preheated to snow-melting temperatures in 20 to 30 min, unless the air temperature is well below 20°F or wind velocity is high (Frier 1965). This short warm-up time makes it unnecessary to turn on the system before snow begins to fall. The equipment can be turned on either manually or with a snow detector. A timer is sometimes used to turn the system off 4 to 6 h after snow stops falling, allowing time for the slab to dry completely.

If the snow is allowed to accumulate before the infrared system is turned on, there will be a delay in clearing the slab, as with embedded hydronic or electric systems. Because infrared energy is absorbed in the top layer of snow rather than by the slab surface, the time needed depends on snow depth and on atmospheric conditions. Generally, a system that maintains a clear slab by melting 1 in. of snow per hour as it falls requires 1 h to clear 1 in. of accumulated snow under the same conditions.

To ensure maximum efficiency, fixtures should be cleaned at least once a year, preferably at the beginning of the winter season. Other maintenance requirements are minimal.

Snow Melting in Gutters and Downspouts

Electrical heating cables are used to prevent heavy snow and ice accumulation on roof overhangs and to prevent ice dams from forming in gutters and downspouts (Lawrie 1966). Figure 10 shows a typical cable layout for protecting a roof edge and downspout. Cable for this purpose is generally rated at approximately 6 to 16 W/ft, and about 2.5 ft of wire is installed per linear foot of roof edge. One foot of heated wire per linear foot of gutter or downspout is usually adequate.

If the roof edge or gutters (or both) are heated, downspouts that carry away melted snow and ice must also be heated. A heated length of cable (weighted, if necessary) is dropped inside the downspout to the bottom, even if it is underground.

Lead wires should be spliced or plugged into the main power line in a waterproof junction box, and a ground wire should be installed from the downspout or gutter. Ground fault circuit protection is required per the *NEC* (NFPA *Standard* 70).

The system can be controlled with a moisture/temperature controller, ambient thermostat, or manual control. The moisture/temperature controller is the most energy efficient. If manual control is used, a protective thermostat should also be used to prevent system operation at ambient temperatures above 41°F.

FREEZE PROTECTION SYSTEMS

If the slab surface temperature is below 32°F, any water film present on that surface freezes. Water may be present because of accidental spillage, runoff from a nearby source, or premature shutoff of snow-melting operation after precipitation ends but before the surface dries (temperature usually drops rapidly after snow). Therefore, for cases with $A_r < 1$, if the system is shut off too soon, the remaining snow and fluid film on the surface may freeze (Adlam 1950). As previously discussed, idling keeps the slab surface from freezing by maintaining a surface temperature of at least 33.5°F and also reduces the required start-up surface heat flux for snow-melting.

INTENSITY ON PAVEMENT FROM FOUR INFRARED FIXTURES, W/ft^2														
14.7	16.0	19.75	23.7	25.5	27.5	28.2	28.0	28.2	27.5	25.5	23.7	19.75	16.0	14.7
23.7	24.8	28.7	31.7	35.7	38.2	38.5	39.4	38.5	38.2	35.7	31.7	28.7	24.8	23.7
25.7	31.7	37.5	42.7	46.4	49.4	52.2	53.0	52.2	49.4	46.4	42.7	37.5	31.7	25.7
28.2	34.3	42.8	46.7	51.2	55.7	58.5	63.0	58.5	55.7	51.2	46.7	42.8	34.3	28.2
28.2	34.3	42.8	46.7	51.2	55.7	58.5	63.0	58.5	55.7	51.2	46.7	42.8	34.3	28.2
25.7	31.7	37.5	42.7	46.4	49.4	52.2	53.0	52.2	49.4	46.4	42.7	37.5	31.7	25.7
23.7	24.8	28.7	31.7	35.7	38.2	38.5	39.4	38.5	38.2	35.7	31.7	28.7	24.8	23.7
14.7	16.0	19.75	23.7	25.5	27.5	28.2	28.0	28.2	27.5	25.5	23.7	19.75	16.0	14.7

Fig. 9   Typical Power Density Distribution for Infrared Snow-Melting System
8 by 15 ft target area, four single-element quartz lamps located
10 ft above floor (Potter 1967).
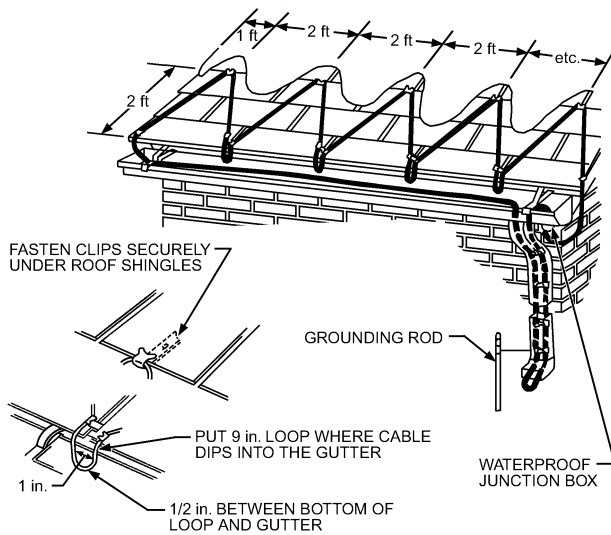
Fig. 10   Typical Insulated Wire Layout to Protect Roof Edge and Downspout

Fig. 11   Typical Heat Tracing Arrangement (Hydronic or Electric)

To calculate surface heat flux during idling, the surface may be assumed to be free of snow, covered with a film of water. Unless there is a constant influx of water from the vicinity, the evaporation heat flux of that film may be ignored and the surface may be assumed to be uncovered because the insulation effect of the water film is negligible. In this case, surface heat flux can be calculated by Equation (5).

The surface is free of snow; therefore, Equation (5) approximates the surface heat flux. The mean radiant temperature that appears in Equation (5) is evaluated using Equations (8), (9), and (10). The fraction F_{sc} of radiation between the surface and the clouds is equal to the cloud cover fraction in the meteorological data.

Chapman (1952) also proposed the following equation to determine the required surface heat flux for idling q_i in Btu/(h · ft²), if the mean ambient air temperature t_m during freezing is known:

$$q_i = (0.27V + 3.3)(32 - t_m) \qquad (23)$$

A slab surface temperature monitor may control the freeze protection system. Whenever the slab surface temperature drops below 33°F, the system activates. However, idling the slab during the entire winter, as given in Table 3, may be too costly—and unnecessary if the main purpose is to reduce high snow-melting surface heat flux at start-up. For example, the annual energy requirement for idling is 45 times more than that for snow-melting in Chicago, $A_r = 0.5$. Therefore, a cost-effective operation may require starting the system to idle only before an anticipated snow. The lead time may be determined by the thermal mass of the slab, local meteorological conditions, idling and start-up snow-melting heat fluxes, and energy cost. Depending on local weather conditions, idling may also be started automatically when prevailing atmospheric conditions make snowfall likely.

Freeze protection systems may also be used in a variety of applications. For example, the foundation of a cold-storage warehouse may be protected from heaving by using a heated floor slab similar to a snow-melting system. The slab must be insulated at the top as well as the back and edges. Top insulation prevents the heated slab from interfering with the space-cooling process in the warehouse. Edge insulation must penetrate below the freezing line. Generally, design heat flux is taken to be between 5 and 10 Btu/(h · ft²) and the system is operated year-round.

Another freeze protection application is pipe tracing, where a pipe or conduit exposed to the atmosphere is protected against
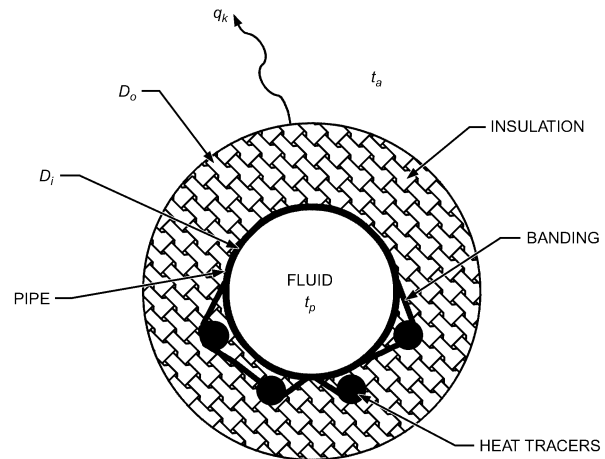
freezing of the fluid within. If a highly viscous fluid is transported, the desired pipe (fluid) temperature may need to be higher than the fluid-freezing temperature to maintain the viscosity required for fluid flow. Figure 11 shows a typical application in which small "tracer" pipes or electrical heating cables are banded along the lower surface of the pipe (Kenny 1999). In a hydronic tracing system, hot fluid or steam may be used. In electric systems, heating cable or mats may be used. Pipe and the tracing elements are covered with thermal insulating material such as fiberglass, polyurethane, calcium silicate, or cellular glass. Sometimes multiple insulation layers may be used. Insulating material must be protected from rain and other external conditions by a weather barrier. Pipe-tracing heat load per unit pipe length q_k is given by the following formula (IEEE 1983):

$$q_k = \frac{(t_p - t_a)}{\dfrac{1}{\pi D_i h_i} + \dfrac{\ln(D_o/D_i)}{2\pi k_1} + \dfrac{\ln(D_3/D_o)}{2\pi k_2} + \dfrac{1}{\pi D_3 h_{co}} + \dfrac{1}{\pi D_3 h_o}} \qquad (24)$$

where

q_k = pipe tracing heat load per unit pipe length, Btu/h·ft

t_p = desired pipe temperature, °F

t_a = design ambient temperature, °F

D_i = inside diameter of inner insulation layer (and outer diameter of pipe), ft

D_o = outside diameter of inner insulation layer (and inside diameter of outer insulation layer, if present), ft

D_3 = outside diameter of outer insulation layer (if present), ft. Otherwise, the expression $\ln(D_3/D_o)/2\pi k_2$ in Equation (24) is dropped and D_3 in the last two terms in the denominator of the same equation is replaced by D_o.

k_1 = thermal conductance of inner insulation layer, Btu/h·ft·°F (evaluated at its average operating temperature)

k_2 = thermal conductance of outer insulation layer, if present, Btu/h·ft·°F (evaluated at its average operating temperature)

h_i = thermal convection coefficient of air film between pipe and inner insulation surface, Btu/h·ft·°F.

h_{co} = thermal convection coefficient of air between outer insulation surface and weather barrier (if present), Btu/h·ft·°F.

h_o = combined surface heat transfer coefficient for radiation and convection between weather barrier, if present (otherwise, the outer insulation layer), to ambient, Btu/h·ft·°F. Values for h_o may be calculated from information in Chapter 3 of the 2005 *ASHRAE Handbook—Fundamentals* and Chapter 15 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment.*
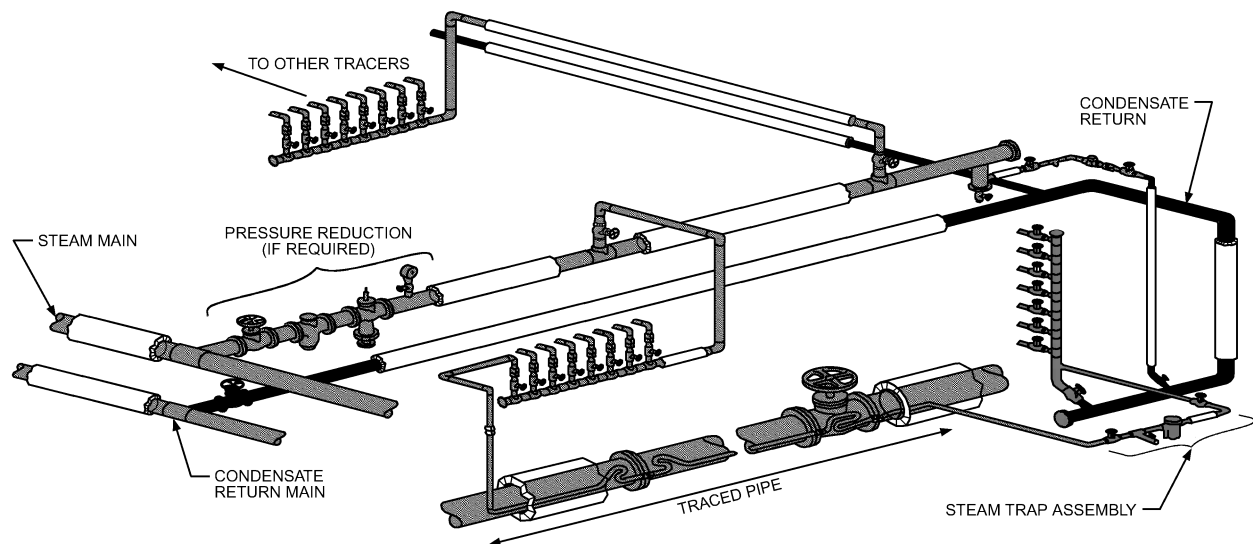
Fig. 12   Typical Pipe-Tracing System with Steam System

An appropriate pipe-tracing system is selected to satisfy q_k. For ease of product selection, some manufacturers offer design software or simple charts and graphs of heat losses for various pipe temperatures and insulation configurations. Safety factors are usually added by explicitly increasing the calculated heat load, by decreasing the design ambient temperature, or by conservative selection of k and h values. Pipe- or conduit-tracing heat loads can be more complex because of the heat sinks that penetrate the insulation surface(s); they often require a complex analysis to determine total heat loss, so a heat trace supplier should be consulted.

Steam Pipe-Tracing Systems

Steam tracing involves circulating steam in a pipe or tube that runs parallel to the pipe being traced. As the steam recondenses, it releases its latent heat and transfers it into the traced pipe. A typical steam pipe-tracing system is shown in Figure 12.

Steam systems have relatively high installed costs, particularly if an appropriately sized boiler and header system is not already in place. Steam is widely used for industrial applications, and the design is familiar to pipe installers. Steam is well suited for applications that require a high heat flux, but often is not as efficient for lower-heat-flux applications such as pipe freeze protection.

Electric Pipe-Tracing Systems

Electric pipe-tracing systems involve placing (tracing) an electrical resistance wire parallel to the pipe or tube being traced. This electric heater provides heat to the pipe to balance heat loss to the lower-ambient surrounding. A typical electric system is shown in Figure 13.

Types of electric heating cables include the following:

• **Self-regulating heating cables** consist of two parallel conductors embedded in a heating core made of conductive polymers. These cables automatically adjust their power output to compensate for local temperature changes. Heat is generated as electric current passes through the conductive core between the conductors. As the pipe temperature drops, the number of electrical paths increases, and more heat is produced. Power output of self-regulating heating cables is specified as watts per unit length at a particular temperature. The self-regulating feature makes the heating cables more energy efficient, because they change their power output based on the need at that point in the pipe. Because they are parallel, they can be cut to length and spliced in the field. Disadvantages are that they
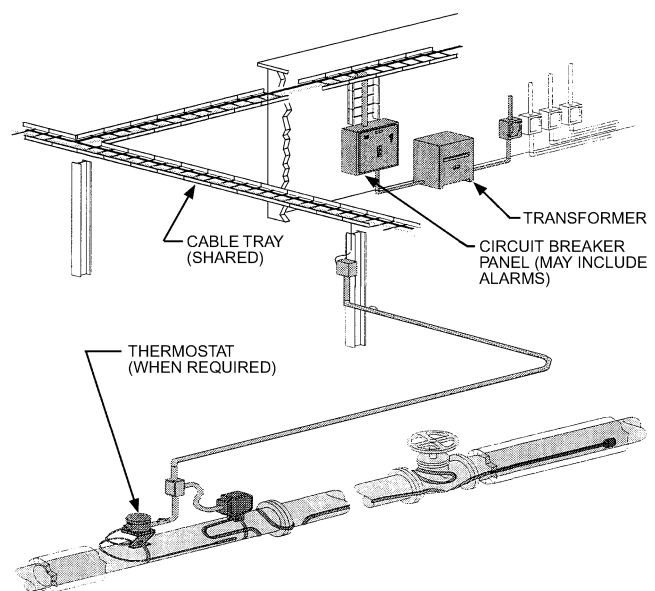
Fig. 13   Typical Pipe Tracing with Electric System

are often more expensive and have shorter maximum run lengths because of inrush current.
• **Series heating cables** are one or two copper, copper alloy, or nichrome elements surrounded by a polymer insulating jacket. Power outputs of series cables are specified in watts per unit length. These heating cables are usually inexpensive. Their main disadvantage is that the length can not be adjusted without changing the power output.
• **Mineral-insulated (MI) heating cables** are series heating cables composed of a magnesium oxide (MgO)-filled, die-drawn cable with one or two copper or copper alloy conductors and a seamless copper or stainless steel alloy sheath. Power output of an MI heating cable is specified in watts per unit length. MI heating cables are rugged and can withstand high temperatures, but are not very flexible. They generally must be ordered in the size needed; splicing in the field is craft-sensitive.
• **Zone heaters** consist of two insulated copper bus wires wrapped with a small-gage (38 to 41 AWG) nichrome heating wire, covered

with polymer insulation. The heating wire is connected to alternate bus wires at nodes spaced 1 to 4 ft apart. Current flowing between the bus wires on the heating element generates heat. Power output of a zone heating cable is specified in watts per unit length. Zone heaters are parallel heaters, and thus can be cut to length and spliced in the field. Care must be used to prevent the thin heating wire from being damaged.

Control

The pipe-tracing system is designed to replace pipe heat loss in the worst case (at the lowest ambient temperature). Most of the time, when the temperature is above the lowest ambient temperature, the heat trace system will produce more heat than is required. To conserve energy, or to prevent the pipe from getting too warm, a control system is usually added.

Approaches to basic control include the following:

- **None.** Sometimes heat trace can be allowed to remain energized, most commonly with short lengths of self-regulating electric heat trace or in cases where the ambient temperature does not change (such as a pipe inside a cold-storage area). This is the least efficient control method from an energy usage standpoint, but the easiest to design. A slight variation on this is a manual switch to disconnect power when not needed, using a switch or circuit breaker.
- **Ambient thermostat.** This involves reading the air temperature and activating the system when the air temperature approaches freezing (often at 40°F). This ensures that the system is energized when the pipe could freeze and de-energized when it is warm. This system is often the best compromise between energy efficiency and ease of design.
- **Pipe-sensing thermostat.** This involves reading the pipe temperature and activating the heat trace system when the pipe temperature approaches freezing (often at 40°F). This is the most energy-efficient system, but is more complex to design so that the sensor reading is representative of all areas of the pipe. Always put the control sensor on the smallest pipe and at the coldest anticipated location.

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CHAPTER 51

EVAPORATIVE COOLING

EVAPORATIVE cooling is energy-efficient, environmentally friendly, and cost-effective in many applications and all climates. Applications range from comfort cooling in residential, agricultural, commercial, and institutional buildings, to industrial applications for spot cooling in mills, foundries, power plants, and other hot environments. Several types of apparatus cool by evaporating water directly in the airstream, including (1) direct evaporative coolers, (2) spray-filled and wetted-surface air washers, (3) sprayed-coil units, and (4) humidifiers. Indirect evaporative cooling equipment combines the evaporative cooling effect in a secondary airstream with a heat exchanger to produce cooling without adding moisture to the primary airstream.

Direct evaporative cooling reduces the dry-bulb temperature and increases the relative humidity of the air. It is most commonly applied to dry climates or to applications requiring high air exchange rates. Innovative schemes combining evaporative cooling with other equipment have resulted in energy-efficient designs.

When temperature and/or humidity must be controlled within narrow limits, heat and mechanical refrigeration can be combined with evaporative cooling in stages. Evaporative cooling equipment, including unitary equipment and air washers, is covered in Chapter 19 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*.

GENERAL APPLICATIONS

Cooling

Evaporative cooling is used in almost all climates. The wet-bulb temperature of the entering airstream limits direct evaporative cooling. The wet-bulb temperature of the secondary airstream limits indirect evaporative cooling.

Design wet-bulb temperatures are rarely higher than 78°F, making direct evaporative cooling economical for spot cooling, kitchens, laundries, agricultural, and industrial applications. At lower wet-bulb temperatures, evaporative cooling can be effectively used for comfort cooling, although some climates may require mechanical refrigeration for part of the year.

Indirect applications lower the air wet-bulb temperature and can produce leaving dry-bulb temperatures that approach the wet-bulb temperature of the secondary airstream. Using room exhaust as secondary air or incorporating precooled air in the secondary airstream lowers the wet-bulb temperature of the secondary air and further enhances the cooling capability of the indirect evaporative cooler.

Direct evaporative cooling is an adiabatic exchange of heat. Heat must be added to evaporate water. The air into which water is evaporated supplies the heat. The dry-bulb temperature is lowered, and sensible cooling results. The amount of heat removed from the air equals the amount of heat absorbed by the water evaporated as heat of vaporization. If water is recirculated in the direct evaporative cooling apparatus, the water temperature in the reservoir approaches the wet-bulb temperature of the air entering the process. By definition, no heat is added to, or extracted from, an adiabatic process; the initial and final conditions fall on a line of constant wet-bulb temperature, which nearly coincides with a line of constant enthalpy.

The maximum reduction in dry-bulb temperature is the difference between the entering air dry- and wet-bulb temperatures. If air is cooled to the wet-bulb temperature, it becomes saturated and the process would be 100% effective. *Effectiveness* is the depression of the dry-bulb temperature of the air leaving the apparatus divided by the difference between the dry- and wet-bulb temperatures of the entering air. Theoretically, adiabatic direct evaporative cooling is less than 100% effective, although evaporative coolers are 85 to 95% (or more) effective.

When a direct evaporative cooling unit alone cannot provide desired conditions, several alternatives can satisfy application requirements and still be energy-effective and economical to operate. The recirculating water supplying the direct evaporative cooling unit can be increased in volume and chilled by mechanical refrigeration to provide lower leaving wet- and dry-bulb temperatures and lower humidity. Compared to the cost of using mechanical refrigeration only, this arrangement reduces operating costs by as much as 25 to 40%. Indirect evaporative cooling applied as a first stage, upstream from a second, direct evaporative stage, reduces both the entering dry- and wet-bulb temperatures before the air enters the direct evaporative cooler. Indirect evaporative cooling may save as much as 60 to 75% or more of the total cost of operating mechanical refrigeration to produce the same cooling effect. Systems may combine indirect evaporative cooling, direct evaporative cooling, heaters, and mechanical refrigeration, in any combination.

The psychrometric chart in Figure 1 illustrates what happens when air is passed through a direct evaporative cooler. In the example shown, assume an entering condition of 95°F db and 75°F wb. The initial difference is 95 – 75 = 20°F. If the effectiveness is 80%, the depression is 0.80 × 20 = 16°F db. The dry-bulb temperature leaving the direct evaporative cooler is 95 – 16 = 79°F. In the adiabatic evaporative cooler, only part of the water recirculated is assumed to evaporate and the water supply is recirculated. The recirculated water will reach an equilibrium temperature approximately the same as the wet-bulb temperature of the entering air.

The performance of an indirect evaporative cooler can also be shown on a psychrometric chart (Figure 1). Many manufacturers define effectiveness similarly for both direct and indirect evaporative cooling equipment. In indirect evaporative cooling, the cooling process in the primary airstream follows a line of constant moisture content (constant dew point). Indirect evaporative cooling effectiveness is the dry-bulb depression in the primary airstream divided by the difference between the entering dry-bulb temperature of the primary airstream and the entering wet-bulb temperature of the secondary air. Depending on heat exchanger design and relative quantities of primary and secondary air, effectiveness ratings may be as high as 85%.

The preparation of this chapter is assigned to TC 5.7, Evaporative Cooling.
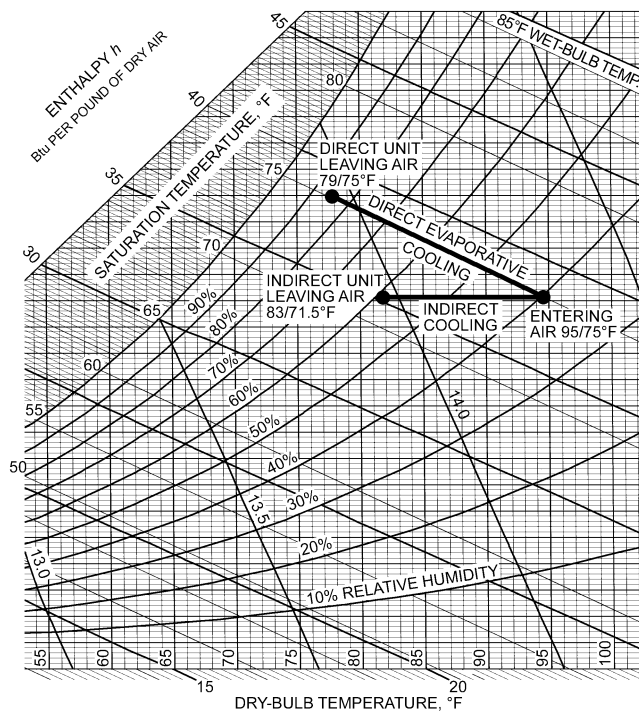
Fig. 1 Psychrometrics of Evaporative Cooling

Assuming 60% effectiveness, and assuming both primary and secondary air enter the apparatus at the outside condition of 95°F db and 75°F wb, the dry-bulb depression is 0.60(95 − 75) = 12°F. The dry-bulb temperature leaving the indirect evaporative cooling process is 95 − 12 = 83°F. Because the process cools without adding moisture, the wet-bulb temperature is also reduced. Plotting on the psychrometric chart shows that the final wet-bulb temperature is 71.5°F. Because both wet- and dry-bulb temperatures in the indirect evaporative cooling process are reduced, indirect evaporative cooling can substitute for part of the refrigeration load in many applications.

Humidification

Air can be humidified with a direct evaporative cooler by three methods: (1) using recirculated water without prior treatment of the air, (2) preheating the air and treating it with recirculated water, or (3) heating recirculated water. Air leaving an evaporative cooler used as either a humidifier or a dehumidifier is substantially saturated when in operation. Usually, the spread between leaving dry- and wet-bulb temperatures is less than 1°F. The temperature difference between leaving air and leaving water depends on the difference between entering dry- and wet-bulb temperatures and on certain physical features, such as the length and height of a spray chamber, cross-sectional area and depth of the wetted media being used, quantity and velocity of air, quantity of water, and spray pattern. In any direct evaporative humidifier installation, air should not enter with a dry-bulb temperature of less than 39°F; otherwise, the water may freeze.

Recirculated Water. Except for the small amount of energy added by shaft work from the recirculating pump and the small amount of heat leakage into the apparatus through the unit enclosure, evaporative humidification is strictly adiabatic. As the recirculated liquid evaporates, its temperature approaches the thermodynamic wet-bulb temperature of the entering air.

The airstream cannot be brought to complete saturation, but its state point changes adiabatically along a line of constant wet-bulb temperature. Typical saturation or humidifying effectiveness of various air washer spray arrangements is between 50 and 98%. The

degree of saturation depends on the extent of contact between air and water. Other conditions being equal, low-velocity airflow is conducive to higher humidifying effectiveness.

Preheated Air. Preheating air increases both the dry- and wet-bulb temperatures and lowers the relative humidity; it does not, however, alter the humidity ratio (i.e., mass ratio of water vapor to dry air) or dew-point temperature of the air. At a higher wet-bulb temperature, but with the same humidity ratio, more water can be absorbed per unit mass of dry air in passing through the direct evaporative humidifier. Analysis of the process that occurs in the direct evaporative humidifier is the same as that for recirculated water. The desired conditions are achieved by heating to the desired wet-bulb temperature and evaporatively cooling at constant wet-bulb temperature to the desired dry-bulb temperature and relative humidity. Relative humidity of the leaving air may be controlled by (1) bypassing air around the direct evaporative humidifier or (2) reducing the number of operating spray nozzles or the area of media wetted.

Heated Recirculated Water. Heating humidifier water increases direct evaporative humidifier effectiveness. When heat is added to the recirculated water, mixing in the direct evaporative humidifier may still be modeled adiabatically. The state point of the mixture should move toward the specific enthalpy of the heated water. By raising the water temperature, the air temperature (both dry- and wet-bulb) may be raised above the dry-bulb temperature of entering air. The relative humidity of leaving air may be controlled by methods similar to those used with preheated air.

Dehumidification and Cooling

Direct evaporative coolers may also be used to cool and dehumidify air. If the entering water temperature is cooled below the entering wet-bulb temperature, both the dry- and wet-bulb temperatures of the leaving air are lowered. Dehumidification results if the leaving water temperature is maintained below the entering air dew point. Moreover, the final water temperature is determined by the sensible and latent heat absorbed from the air and the amount of circulated water, and it is 1 to 2°F below the final required dew-point temperature.

The air leaving a direct evaporative cooler being used as a dehumidifier is substantially saturated. Usually, the spread between dry- and wet-bulb temperatures is less than 1°F. The temperature difference between leaving air and leaving water depends on the difference between entering dry- and wet-bulb temperatures and on certain design features, such as the cross-sectional area and depth of the media or spray chamber, quantity and velocity of air, quantity of water, and the water distribution.

Air Cleaning

Direct evaporative coolers of all types perform some air cleaning. Rigid-media direct evaporative coolers are effective at removing particles down to about 1 μm in size. Air washers are effective down to about 10 μm.

The dust removal efficiency of direct evaporative coolers depends largely on the size, density, wettability, and solubility of the dust particles. Larger, more wettable particles are the easiest to remove. Separation is largely a result of impingement of particles on the wetted surface of the eliminator plates or on the media surface. Because the force of impact increases with the size of the solid, the impact (together with the adhesive quality of the wetted surface) determines the cooler's usefulness as a dust remover. The standard low-pressure spray is relatively ineffective in removing most atmospheric dusts. Direct evaporative coolers are of little use in removing soot particles because their greasy surface does not adhere to the wet plates or media. Direct evaporative coolers are also ineffective in removing smoke, because the small particles (less than 1 μm) do not impinge with sufficient force to pierce the water film and be held on the media. Instead, the particles follow the air path between the media surfaces.

Control of Gaseous Contaminants. When used in a makeup air system comprised of a mixture of outside air and recirculated air, direct evaporative coolers function as scrubbers and reduce some gaseous contaminants found in outside air. These contaminants may concentrate in the recirculating water, so some water needs to be bled off. For more information regarding the control of gaseous contaminants, see Chapter 45.

INDIRECT EVAPORATIVE COOLING SYSTEMS FOR COMFORT COOLING

Five types of indirect evaporative cooling systems are most commonly used for commercial, institutional and industrial cooling applications. Figures 2 to 6 show schematics of these dry evaporative cooling systems.

Indirect evaporative cooling efficiency is measured by the approach of the outdoor air dry-bulb condition to either the room return air or scavenger outdoor air wet-bulb condition on the wet side of the air-to-air heat exchanger. The **indirect evaporative cooling effectiveness (IEE)** is expressed as follows:

$$IEE = \frac{t_1 - t_2}{t_1 - t_3} \times 100$$

where

t_1 = supply air inlet dry-bulb temperature, °F
t_2 = supply air outlet dry-bulb temperature, °F
t_3 = wet-side air inlet wet-bulb temperature, °F

The heat pipe air-to-air heat exchanger in Figure 2 uses a direct water spray from a recirculation sump on the wet side of the heat pipe tubes (Scofield and Taylor 1986). When either room return or scavenger outdoor air passes over the wet surface, outdoor air entering the building is dry-cooled and produces an approach to the wet-side wet-bulb temperature in the range of 60 to 80% IEE for equal mass flow rates on both sides of the heat exchanger. The IEE is a function of heat exchanger surface area, face velocity, and completeness of wetting achieved for the wet-side heat exchanger surface. Face velocities on the wet side are usually selected in the range of 400 to 450 fpm.

Figure 3 shows a cross-flow plate type air-to-air indirect evaporative cooling heat exchanger (Yellott and Gamero 1984). In this configuration, outdoor air is supplied by a single fan for both wet- and dry-side flows through the heat exchanger. Recirculation water from the sump below the heat exchanger is sprayed downward
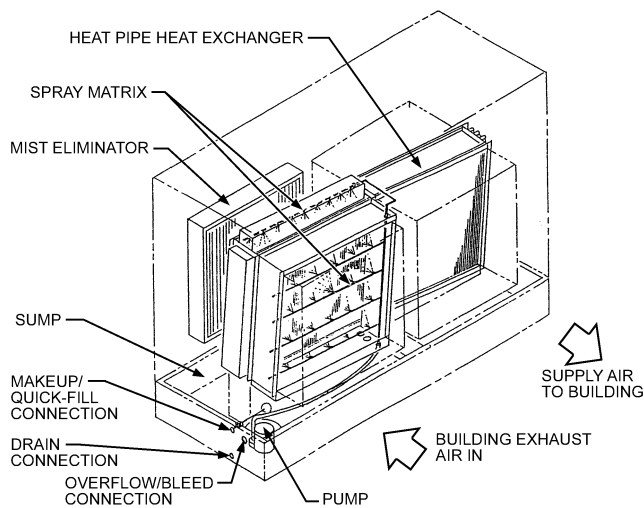
through the vertical wet-side air path, counterflow to the air which moves vertically up through the heat exchanger. The horizontal airflow path is dry-cooled with a 60 to 80% IEE for equal mass flows on both sides of the heat exchanger. Again, the approach to the ambient wet bulb is a function of heat exchanger surface area and the effectiveness of the water spray system at completely wetting the wet-side surface of the air-to-air heat exchanger.

The heat wheel (Figure 4) and the run-around coil system (Figure 5) both use a direct evaporative cooling component on the cold side to enhance the dry-cooling effect on the makeup air side. The heat wheel (sensible transfer), when sized for 500 fpm face velocity with equal mass flows on both sides, has an IEE around 60 to 70%. The run-around coil system at the same conditions produces an IEE of 35 to 50%. The adiabatic cooling component is usually selected for an effectiveness of 85 to 95%. Water coil freeze protection is required in cold climates for the run-around coil loop.

Air-to-air heat exchangers that are directly wetted produce a closer approach to the wet-side wet-bulb temperature, all things being equal. First cost, physical size, and parasitic losses are also reduced by direct wetting of the heat exchanger. In applications having extremely hard makeup water conditions, using a direct evaporative cooling device in lieu of directly wetting the air-to-air heat exchanger may reduce maintenance costs and extend the useful life of the system.

All of the air-to-air heat exchangers (Figures 2 to 5) produce beneficial winter heat recovery when using building return air with the sprays or adiabatic cooling component turned off.

PLAN VIEW   END VIEW   SIDE VIEW
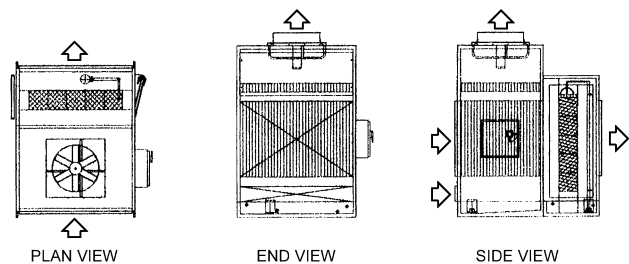
Fig. 3   Cross-Flow Plate Air-to-Air Indirect Evaporative Cooling Heat Exchanger

Fig. 2   Heat Pipe Air-to-Air Heat Exchanger with Sump Base
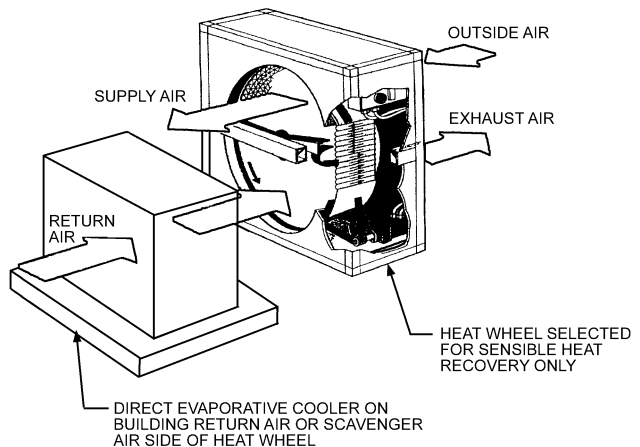
Fig. 4   Rotary Heat Exchanger with Direct Evaporative Cooling

Figure 6 shows a cooling-tower-to-coil indirect evaporative cooling system with IEE in the range of 50 to 75% (Colvin 1995). The cooling tower is selected for a close approach to the ambient wet-bulb temperature, with sump water from the tower then pumped to precooling coils in an air-handling unit. Provision for water filtration to remove solids from sump water is needed, and water coils may need to be cleanable. Freeze protection of the water coil loop is required in cold climates. No winter heat recovery is available with this design.

Table 1 gives the designer some performance predictions and application limits that may be helpful in determining the indirect evaporative cooling system that best solves the design problem at hand. If winter heat recovery is a priority, the heat wheel system may provide the quickest payback. Runaround coil systems are applied where supply air and exhaust air ducts are remote from each other. The heat pipe adapts well to high-volume air-handling systems where cooling energy reduction is the priority. The plate heat exchanger fits smaller-volume systems with high cooling requirements but with lower winter heat recovery potential.

Indirect Evaporative Cooling Controls

Where the heat exchanger is directly wetted, a water hardness monitor for the recirculation water sump is recommended. Water hardness should be kept within 200 to 500 parts per million (ppm) to minimize plating out of dissolved solids from the sump. To maintain its set point, the hardness monitor may initiate a sump dump cycle when it detects increased water hardness. In addition, the sump should have provisions for a fixed bleed so that extra makeup water is continuously introduced to dilute dissolved solids left behind when water evaporates from the wetted heat exchanger surface. Sumps should always be drained at the end of a duty cycle and refilled the next day when the system is turned on. For rooftop applications, sumps should be drained for freeze protection during low ambient temperatures.

Air-side control for a cooling system with a 55°F supply air set point may be set up as follows. The heat exchanger's cold-side sprays or direct evaporative cooling component should be activated whenever ambient dry-bulb temperatures exceed 65°F, if room return air is used on the wet-side of the air-to-air heat exchanger. Air-conditioned buildings have a stable return air wet-bulb condition in the range of 60 to 65°F. Valuable precooling of outdoor air may be achieved when ambient dry-bulb temperatures exceed the return air wet-bulb condition.

Where outdoor air is used on the cold-air side of the heat exchanger, cooling may begin at ambient temperatures above 55°F, because the wet-bulb condition of outdoor air is always lower than its dry-bulb condition.

Parasitic losses generated by the heat exchanger static pressure penalty to supply and return air fans and by the water pump need to be evaluated. These losses may be mitigated by opening bypass dampers around the heat exchanger for pressure relief and shutting off the pump in the ambient temperature range of 55 to 65°F db. Where scavenger outdoor air is used on the cold side of an air-to-air heat exchanger, this temperature range may be reduced somewhat. A comparison of the energy penalty to the precooling energy avoided determines the optimum range of ambient conditions for this control strategy.

For variable-air-volume (VAV) supply and return fan systems, the static penalty reduces by the square of the airflow reduction from full design flow at summer peak design condition. As airflow rates decrease across an air-to-air heat exchanger, the IEE increases, thereby providing better precooling. Where scavenger outdoor air is used for indirect evaporative cooling, the wet-side airflow rate is usually constant volume.
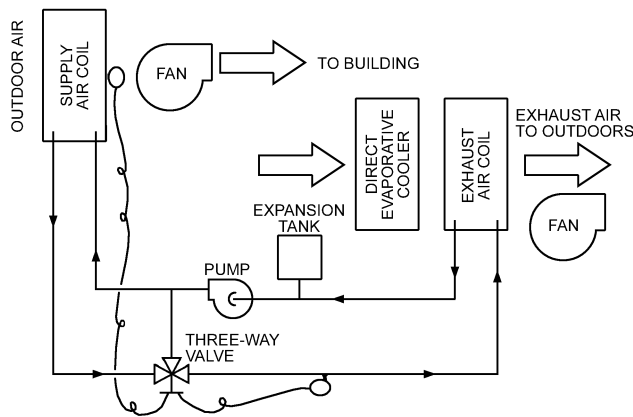
Fig. 5   Coil Energy Recovery Loop with Direct Evaporative Cooling
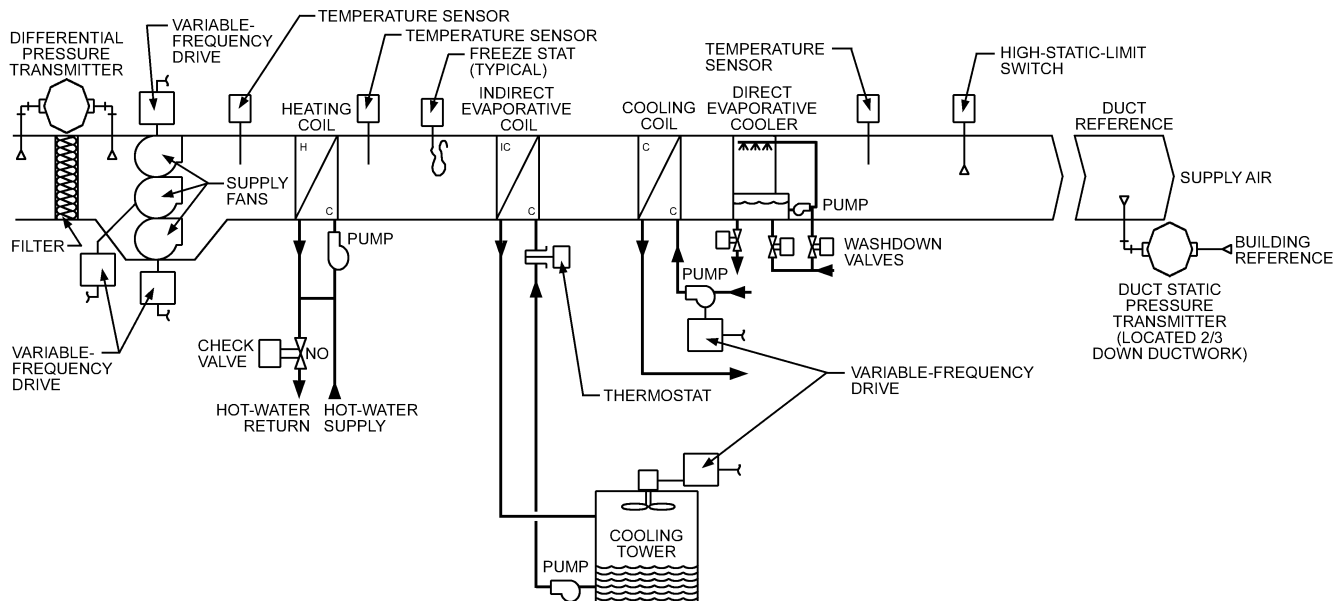
Fig. 6   Cooling-Tower-to-Coil Indirect Evaporative Cooling

Table 1 Indirect Evaporative Cooling Systems Comparison

System Type[a]	WBDE,[b] %	Heat Recovery Efficiency, %	Wet-Side Air ΔP, in. of water	Dry-Side Air ΔP, in. of water	Pump hp per 10,000 cfm	Parasitic Loss Range,[e] KW/ton of Cooling	Equipment Cost Range,[f] $/Supply cfm	Notes
Cooling tower to coil	40 to 60	NA	NA	0.4 to 0.7	Varies	Varies	0.50 to 1.00	Best for serving multiple AHUs from a single cooling tower. No winter heat recovery.
Crossflow plate	60 to 85	40 to 50	0.7 to 1.0	0.4 to 0.7	0.1 to 0.2	0.12 to 0.20	1.20 to 1.70	Most cost-effective for lower airflows. Some cross contamination possible. Low winter heat recovery.
Heat pipe[c]	65 to 75	50 to 60	0.7 to 1.0	0.5 to 0.7	0.2 to 0.4	0.15 to 0.25	1.50 to 2.50	Most cost-effective for large airflows. Some cross contamination possible. Medium winter heat recovery.
Heat wheel[d]	60 to 70	70 to 80	0.6 to 0.9	0.4 to 0.65	0.1 to 0.2	0.2 to 0.3	1.50 to 2.50	Best for high airflows. Some cross contamination. Highest winter heat recovery rates.
Runaround coil[δ]	35 to 50	40 to 60	0.6 to 0.8	0.4 to 0.6	Varies	> 0.35	1.00 to 2.00	Best for applications where supply and return air ducts are separated. Lowest summer WBDE.

WBDE = wet-bulb depression efficiency

Notes:

[a]All air-to-air heat exchangers have equal mass flow on supply and exhaust sides.
[b]Plate and heat pipe are direct spray on exhaust side. Heat wheel and runaround coil systems use 90% WBDE direct evaporative cooling media on exhaust air side.

[c]Assumes six-row heat pipe, 11 fpi, with 500 fpm face velocity on both sides.
[d]Assumes 500 fpm face velocity. Parasitic loss includes wheel rotational power.
[e]Includes air-side static pressure and pumping penalty.
[f]Excludes cooling tower cost and assumes less than 200 ft piping between components.
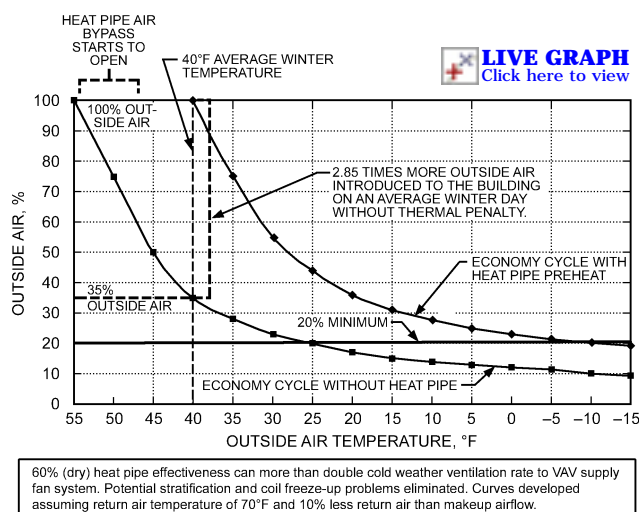
Fig. 7 Increased Winter Ventilation

Winter heat recovery may be initiated at ambient temperatures below the 55°F supply air set point. Where building return air is used with an air-to-air heat exchanger, the 70 to 75°F return air condition is used to preheat makeup air for the building. For a VAV supply air system, Figure 7 shows the increased ventilation potential of a heat pipe air-to-air heat exchanger that uses face and bypass dampers on the supply air side to mix unheated outdoor air with preheated outdoor air to maintain the 55°F building supply air set point (Scofield and Bergman 1997). The heat pipe leaving air temperature may also be controlled with a tilt control (see Chapter 44 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*). With a heat pipe economizer, a minimum outdoor air ventilation rate of 20% would not be breached until ambient temperatures dropped below –15°F.

Runaround coils control leaving supply air temperature with a three-way valve (see Figure 5). Because of their higher parasitic losses, these systems may require a wider range of ambient conditions where pressure-relief bypass dampers are open and the pump system shut down. Some projects limit activation of these recovery systems to ambient temperatures above 85°F to below 40°F.

Indirect/Direct Evaporative Cooling with VAV Delivery

Coupling indirect and direct evaporative cooling to a variable-air-volume (VAV) delivery system in arid climates can effectively eliminate requirements for mechanical refrigeration cooling in many applications. Many cities in the western United States have summer design conditions suitable to deliver 55°F or lower supply air to a building using a 70% IEE indirect and a 90% effective direct evaporative cooling system.

Figure 8 shows plan and elevation views of an air-handling unit using a sprayed heat pipe air-to-air heat exchanger and a wetted-media direct evaporative cooling section augmented by a final-stage chilled-water cooling coil (Scofield and Bergman 1997). The 70% indirect IEE is achieved with a direct-sprayed heat pipe using a sump and a recirculation water system on the building return air side of the heat exchanger. The 90% effective direct evaporative cooling medium is split into two sections for two-stage cooling capacity control of the 55°F leaving air temperature. The direct evaporative cooling system also uses a sump and water recirculation. Supply-side heat pipe face and bypass dampers control the final supply air temperature (55°F) in both summer (when indirect sprays are on) and winter, to control the heat pipe's heat recovery capacity. Heat pipe dampers on both sides of the heat exchanger are powered to full open to mitigate system parasitic losses during ambient temperature conditions when the value of energy recovered is exceeded by the fan energy penalty. The recirculation damper is used for morning warm-up of the building and for blending building return air with preheated outdoor air during extreme cold ambient conditions (see Figure 7).

Table 2 uses ASHRAE bin weather data for the semi-arid climate of Sacramento, California, to illustrate potential cooling energy savings for a 10,000 cfm VAV design that turns down to 5000 cfm at winter design (Scofield and Bergman 1997). Compared to a conventional-refrigeration cooling VAV design with a 25% minimum outdoor air economizer, the two-stage evaporative cooling system reduces peak cooling load by 49% while introducing 100% outdoor air. For a building duty cycle of 8760 h per year, the ton-hour savings is $34,037, or a 60% reduction compared to the conventional air-side economizer system with mechanical cooling only. Within ambient bin conditions of 62°F db/54°F wb to 57°F db/52°F wb, there are 2376 cooling hours per year (27% of the annual cooling hours) where a 90% wet-bulb depression efficiency (WBDE) direct evaporative cooling system may be used for the 55°F supply air requirement without refrigeration.

PLAN VIEW

SIDE VIEW

Packaged rooftop variable-air-volume units can increase ventilation in winter and reduce cooling costs while introducing 100% outdoor air in warmer weather.

*12 in. deep, 90% saturation efficiency cooling media split 4 in. (upstream) and 8 in. (downstream) in the direction of airflow for cooling and humidification capacity control.
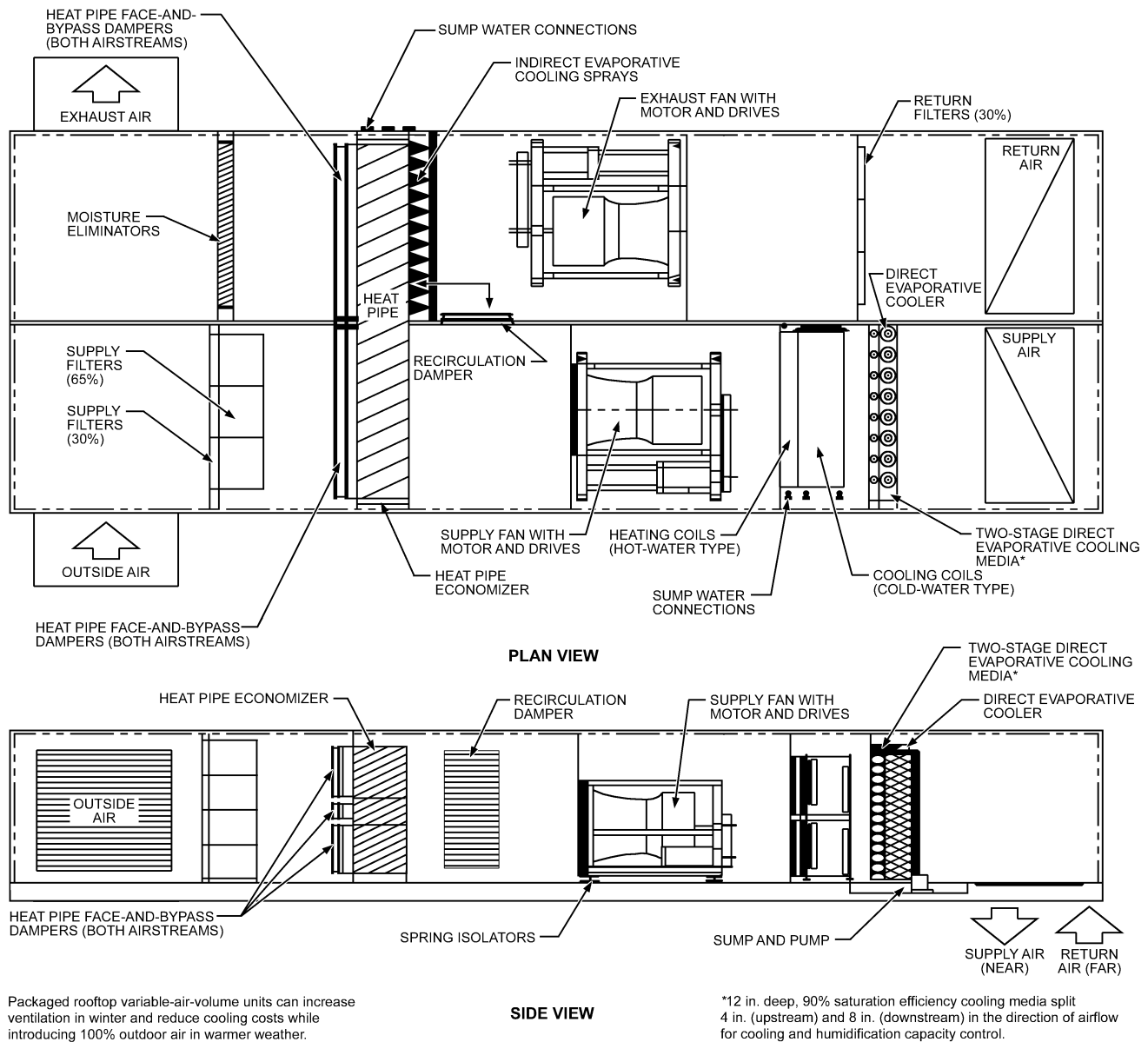
Fig. 8   Heat Pipe Air-Handling Unit

Figure 9 uses typical meteorological year (TMY) data for 14 cities in the western United States to illustrate the evaporative cooling annual refrigeration avoidance per 10,000 cfm of VAV supply air, compared to a 25% minimum outdoor air economizer (Scofield and Bergman 1997). For thermal energy storage (TES) applications, the two-stage evaporative cooling design may significantly reduce chiller plant storage capacity and refrigeration equipment first cost.

Benefits of this design in dry climates include the following:

- Indoor air quality is improved by using all outdoor air during cooling, and increased ventilation in winter through the heat pipe economizer (see Figure 7).
- Energy demand is in the range of 0.15 to 0.25 kW per ton of cooling, versus air-cooled refrigeration at 1.2 to 1.3 kW per ton.
- Peak building electrical cooling and gas heating demand requirements are reduced, especially for applications that require higher amounts of outdoor air.
- Because VAV pinchdown terminals may reduce their minimum airflow settings and comply with ASHRAE *Standard* 62.1,

supply and return fan energy savings are possible in cooler weather when using an all-outdoor-air design.

- VAV turndown of fans during cooler ambient conditions decreases fan parasitic energy losses because of the evaporative cooling system components.
- VAV turndown increases the IEE of both the air-to-air heat exchanger and direct evaporative cooling system.
- In semi-arid climates where a chilled-water final cooling stage is required, two-stage evaporative cooling allows central chilled-water plants to be turned off earlier in the fall and reactivated later in the spring. This results in significant maintenance and cooling energy cost savings.
- In cooler weather, resetting supply air down to 50°F and using only the direct evaporative cooler extends free cooling hours and reduces fan energy.
- When using building return air, winter heat recovery provides increased outdoor air quantities during the period when fan turndown can result in loss of proper ventilation rates for VAV systems (see Figure 7).

Table 2 Sacramento, California, Cooling Load Comparison

Outdoor Air db/wb, °F	VAV Supply, cfm	Hours Per Year[d]	100% Outdoor Air Indirect-Direct Evaporative Cooling				25% Outdoor Air Economizer		
			Indirect LAT db/wb, °F	Direct LAT db/wb, °F	Refrigeration,[a] tons	Refrigeration,[b] ton·h	Mixed Air db/wb, °F	Refrigeration,[a] tons	Refrigeration,[b] ton·h
107/70	10,000	7	76.9/60	61.7/60	14.2	99.4	83/65.5	29.2	204.4
102/70	9,688	59	75.4/61.3	62.7/61.3	17.4	1026.6	81.8/65.5	28.3	1669.7
97/68	9,375	144	73.9/60.1	61.5/60.1	14	2016	80.5/65.0	25.9	3729.6
92/66	9,062	242	72.4/59.1	60.4/59.1	11.5	2783	79.2/64.5	23.7	5735.4
87/65	8,750	301	70.9/59.3	60.5/59.3	10.5	3160.5	78/64.3	22.3	6712.3
82/63	8,438	397	69.4/58.7	59.8/58.7	9.5	3771.5	76.8/63.9	20.3	8059.1
77/61	8,125	497	67.9/57.7	58.7/57.7	6.7	3329.9	77.5/63.3	18.3	9095.1
72/59	7,812	641	66.4/56.8	57.8/56.8	5.3	3397.3	72/59[b]	12.9	8268.9
67/57	7,500	821	64.9/56.0	56.9/56.0	3.9	3201.9	67/57[b]	9	7389
62/54	7,188	1086	62/54	54.8/54	0	0	62/54[b]	4.3	4669.8[c]
57/52	6,875	1290	57/52	52.5/52	0	0	57/52[b]	1	1290[c]
					Total ton·h =	22,786.1		Total ton·h =	56,823.3

LAT = leaving-air temperature
Notes:
[a]Amount of cooling required to reach 55°F db supply air requirements.
[b]Ambient conditions when dampers for air-side economizer introduce 100% outdoor air in arid climates.

[c]Ambient conditions when 90% saturation efficiency direct evaporative cooler may be used to eliminate refrigeration cooling. Heat pipe bypass dampers should be open to minimize parasitic losses. Indirect water sprays should be off.
[d]Bin hours at each condition based on 24 h/day, 365 day/year duty cycle.

Table 3 Sacramento, California, Heat Recovery and Humidification

Outdoor Air db/wb, °F	VAV Supply,[a] cfm	Hours Per Year[b]	Heat Recovery Leaving Air db/wb, °F	Direct Evaporative Humidifier Leaving Air db/wb,[c] °F	Energy Savings,[d] Btu/h	Resultant Room rh
52/48	6562	1199	62.8/52.7	55/52.7	73,822	54%
47/44	6250	924	60.8/50.5	55/50.5	90,000	47%
42/40	5938	660	58.8/48.1	55/48.1	98,868	38%
37/36	5625	333	56.8/46.0	55/46.0	120,285	32%
32/31	5312	116	54.8/43.2	OFF	130,803	25%[e]
27/26	5000	30	52.8/41.0	OFF	250,776	21%[e]

Notes:
[a]VAV turndown airflow is assumed linear from summer design (10,000 cfm) to winter design (5000 cfm).
[b]Bin hours at each condition based on 24 h/day, 365 days/year duty cycle.
[c]Heat pipe overheats outdoor air to allow direct evaporative humidifier to add moisture.

[d]Recirculated building heat used for preheating 100% outdoor air and increasing humidity levels.
[e]Additional heat is required or recirculation damper must open during these bin conditions, to maintain both acceptable 30% indoor relative humidity and reach the 55°F supply air set point.

Note: Fourteen Western cities where indirect/direct evaporative cooling systems, using heat pipe (wet) indirect evaporative effectiveness of 70% and direct evaporative cooler saturation efficiency of 90%, can be used to introduce 100% outdoor air, with substantial reductions in ton-hour cooling requirements compared to conventional 24% outdoor air economizer damper design. Ton-hour totals for each system based on 24 h/day, 365 day/year duty cycle and 10,000 cfm VAV supply air. NREL hour by hour TMY data used to develop ton-hours listed. Fan heat not included.

Fig. 9 Refrigeration Reduction with Two-Stage Evaporative Cooling Design

• During mild winter daytime ambient conditions, the 4 in. deep wetted media section may be used for beneficial building humidification (see Table 3).

Beneficial Humidification

Areas with mild winter climates (e.g., the western U.S. coast) may use the heat available in building return air, through the air-to-air heat exchanger, to overheat supply air and add building humidification during the driest season of the year. The 4 in. section of direct evaporative cooling media (see Figure 8) is used in cool ambient conditions as a humidifier. Table 3 (Scofield and Bergman 1997) extends the Table 2 bin weather data for the Sacramento, California, site into winter ambient conditions. The table shows that 100% outdoor air may be introduced and humidity controlled between 54 and 32% for ambient conditions down to 37°F with a 60% heat pipe recovery effectiveness. ASHRAE *Standard* 62.1 recommends that humidities in occupied areas be maintained between 30 and 60% rh. There are only 146 bin hours below the 37°F ambient threshold during which the building recirculation air damper (see Figure 8) would have to open or additional heat be added with the hot-water coil to maintain the 55°F air delivery set point. The average winter temperature in Sacramento is 52.7°F, which is fairly typical for this region.

Indirect Evaporative Cooling With Heat Recovery

In indirect evaporative cooling, outside supply air passes through an air-to-air heat exchanger and is cooled by evaporatively cooled air exhausted from the building or application. The two airstreams never mix or come into contact, so no moisture is added to the supply air stream. Cooling the building's exhaust air results in a

City	Outside Air Design db/wb, °F	Indirect db/wb, °F	Supply Air db, °F	Two-Stage Sensible Capacity, Btu/h	Two-Stage Sensible EER	EUC, %
				Indirect/Direct Performance (Supply Air: 400 scfm)		
Los Angeles, CA	85/64	72.4/59.6	61.8	7862	39.3	22.0
San Francisco, CA	83/63	71.0/58.7	60.9	8265	41.3	20.9
Seattle, WA	85/65	73.0/60.9	63.1	7314	36.6	23.6
Albuquerque, NM	96/60	74.4/52.5	55.7	10,515	52.6	16.4
Denver, CO	93/60	73.2/53.2	56.1	10,306	51.5	16.8
Salt Lake City, UT	96/62	75.6/55.1	58.1	9470	47.3	18.2
Phoenix, AZ	110/70	86.0/62.5	65.8	6131	30.7	28.2
El Paso, TX	101/64	78.8/56.7	59.9	8703	43.5	19.9
Santa Rosa, CA	85/67	74.2/63.5	65.5	6261	31.3	27.6
Spokane, WA	92/62	74.0/55.7	58.4	9315	46.6	18.6
Boise, ID	96/63	76.2/56.2	59.2	9007	45.0	19.2
Billings, MT	93/63	75.0/57.0	59.7	8759	43.8	19.7
Portland, OR	90/67	76.2/62.4	64.7	6590	32.9	26.2
Sacramento, CA	100/69	81.4/63.0	65.8	6141	30.7	28.1
Fresno, CA	103/71	83.8/65.1	67.9	5216	26.1	33.1
Austin, TX	98/74	83.6/70.0	72.3	3337	16.7	51.8

Notes:
I/D effectiveness: Indirect = 60% or 0.6 (dry bulb – wet bulb);
  Direct = 90% or 0.9 (dry bulb – wet bulb).
Outdoor air design condition: 0.4% dry bulb/mean coincident wet bulb (2005 *ASHRAE Handbook—Fundamentals*, Chapter 28).
Fan heat is added to two-stage supply air dry bulb (0.9°F)
Assume 0.3 W/cfm for the direct and 0.2 W/scfm for the indirect section (200 W total). AC is 1000 W in all cases.
Sensible capacity = 1.08 × scfm × Δt. For AC, this is 8640 Btu/h in all cases, based on 20°F Δt.
EER = energy efficiency ratio = Btu/h cooling output per watt of electrical input. Comparison base to conventional refrigeration with 60°F supply air and 20°F temperature drop.
Sensible EER = Sensible cooling capacity ÷ wattage.
EUC = Energy Use Comparison to conventional refrigeration with EER = 8.6.
Psychrometric routines calculated using site atmospheric pressure.

Fig. 10 Indirect/Direct Two-Stage System Performance

larger overall temperature difference across the heat exchanger and a greater cooling of the supply air. Indirect evaporative cooling requires only fan and water pumping power, so the coefficient of performance tends to be high. The principle of indirect evaporative cooling is effective in most air-conditioned buildings, because evaporative cooling is applied to exhaust air rather than to outside air.

Indirect evaporative cooling has been applied in a number of heat recovery applications (Mathur et al. 1993), such as plate heat exchangers (Scofield and DesChamps 1984; Wu and Yellot 1987), heat pipe exchangers (Mathur 1998; Scofield 1986), rotary regenerative heat exchangers, and two-phase thermosiphon loop heat exchangers (Mathur 1990). In residential air conditioning, the outside condensing unit can be evaporatively cooled to enhance performance (Mathur 1997; Mathur and Goswami 1995; Mathur et al. 1993). Indirect evaporative cooling with heat recovery is covered in detail in Chapter 44 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*.

BOOSTER REFRIGERATION

Staged evaporative coolers can completely cool office buildings, schools, gymnasiums, sports facilities, department stores, restaurants, factory space, and other buildings. These coolers can control room dry-bulb temperature and relative humidity, even though one stage is a direct evaporative cooling stage. In many cases, booster refrigeration is not required. Supple (1982) showed that even in higher-humidity areas with a 1% mean wet-bulb design temperature of 75°F, 42% of the annual cooling load can be satisfied by two-stage evaporative cooling. Refrigerated cooling need supply only 58% of the load.

Figure 10 shows indirect/direct two-stage performance for 16 cities in the United States. Performance is based on 60% effectiveness of the indirect stage and 90% for the direct stage. Supply air temperatures (leaving the direct stage) at the 0.4% design dry-bulb mean coincident wet-bulb condition range from 56.1 to 72.3°F. Energy use ranges from 16.4 to 51.8%, compared to conventional refrigerated equipment.

Booster mechanical refrigeration provides inside design comfort conditions regardless of the outside wet-bulb temperature without having to size the mechanical refrigeration equipment for the total cooling load. If the inside humidity level becomes uncomfortable, the quantity of moisture introduced into the airstream must be limited to control room humidity. Where the upper relative humidity design level is critical, a life-cycle cost analysis favors a design with an indirect cooling stage and a mechanical refrigeration stage.

Figure 11 shows an air-handling unit design that uses building return air instead of outdoor air to develop the indirect (dry) evaporative cooling effect with a direct-sprayed, heat pipe, air-to-air, heat exchanger (Felver et al. 2001). The humid, cool air off the heat pipe is then used to reject the heat of refrigeration at a condenser coil downstream of the exhaust fan. The direct expansion (DX) cooling coil, the last component in the supply air, develops the final building supply air temperature when the two-stage evaporative cooling components cannot meet the design cooling requirements. Figure 12 shows the process points for both supply and exhaust airstreams, using the Stockton, California, ASHRAE 0.4% summer dry-bulb design ambient condition. Several benefits accrue from this evaporative cooling design:

- Building return air has a more predictable and stable wet-bulb condition (60 to 65°F) than ambient air for use in generating the first stage of indirect (dry) evaporative cooling. Daytime absorption of moisture inside most buildings further enhances the first-stage cooling effect.
- Locating a DX condenser coil in sprayed exhaust off the heat pipe results in a more efficient rejection of refrigeration heat than a condenser coil located outdoors in the ambient air.
- Lower refrigeration condensing temperatures increase compressor capacity and compressor life, and reduce energy consumption.
- Central chilled-water plant or remote chiller installation and piping costs are eliminated.
- Evaporative cooling components provide back-up cooling capability in case of compressor failure. Figure 12 shows equilibrium

conditions in the occupied area with indirect/direct evaporative cooling only.

- Peak refrigeration demand can be reduced 14 to 40% in California's semi-arid climate (Scofield 1994).
- Blow-through supply fan and draw-through exhaust fans provide:

  - Reduced supply fan heat addition for DX cooling system.
  - Reduced risk of cross contamination of supply air with exhaust air for hospital or laboratory applications.
  - Reduced fan noise breakout into building duct system.
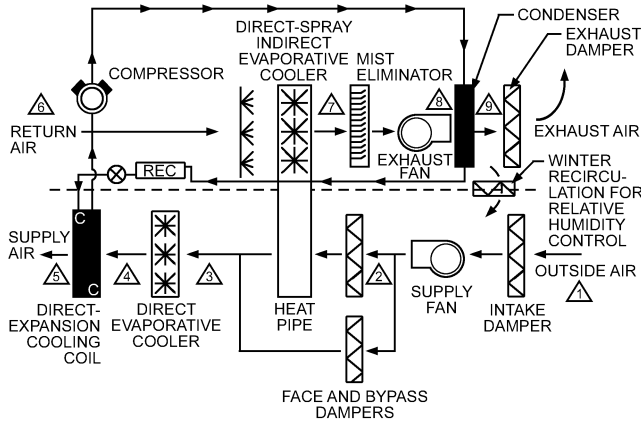
PSYCHROMETRIC STATE POINTS:

1. 100°F db/69°F wb	4. 61.7°F db/60.4°F wb	7. 72.8°F db/72.5°F wb
2. 103°F db/69.9°F wb	5. 55°F db/55°F wb	8. 75°F db/73.1°F wb
3. 74°F db/60.4°F wb	6. 75°F db/63°F wb	9. 95°F db/78.4°F wb

Fig. 11   Two-Stage Evaporative Cooling with Third-Stage Integral DX Cooling Design

There are several design considerations for the successful integration of DX refrigeration with two-stage evaporative cooling air-handling units, as shown in Figure 11.

For both constant-volume (CV) and variable-air-volume (VAV) units, the return air must closely match the supply airflow to ensure adequate heat rejection at the condenser coil. Buildings with large fixed-exhaust systems may not provide sufficient building return airflow for absorption of refrigeration heat at acceptable refrigerant condensing temperatures.

Face-and-bypass dampers are required around the condenser coil for control of the refrigerant condensing pressure and temperature.

Note that peak refrigeration requirements always occur during the highest ambient humidity (dew-point design) conditions. In semi-arid climates, this design condition occurs during reduced summer ambient dry-bulb temperatures (Ecodyne Corp. 1980). Review of site ASHRAE dew-point design conditions (Chapter 28 of the 2005 *ASHRAE Handbook—Fundamentals*) is required to determine the peak refrigeration cooling capacity needed to maintain the specified supply air temperature set point to the building.

RESIDENTIAL OR COMMERCIAL COOLING

In dry climates, evaporative cooling is effective at lower air velocities than those required in humid climates. Packaged direct evaporative coolers are used for residential and commercial application. Cooler capacity may be determined from standard heat gain calculations (see Chapters 29 and 30 of the 2005 *ASHRAE Handbook—Fundamentals*).

Detailed calculation of heat load, however, is usually not economically justified. Instead, one of several estimates gives satisfactory results. In one method, the difference between dry-bulb design temperature and coincident wet-bulb temperature divided by 10 is equal to the number of minutes needed for each air change. This or any other arbitrary method for equating cooling capacity with
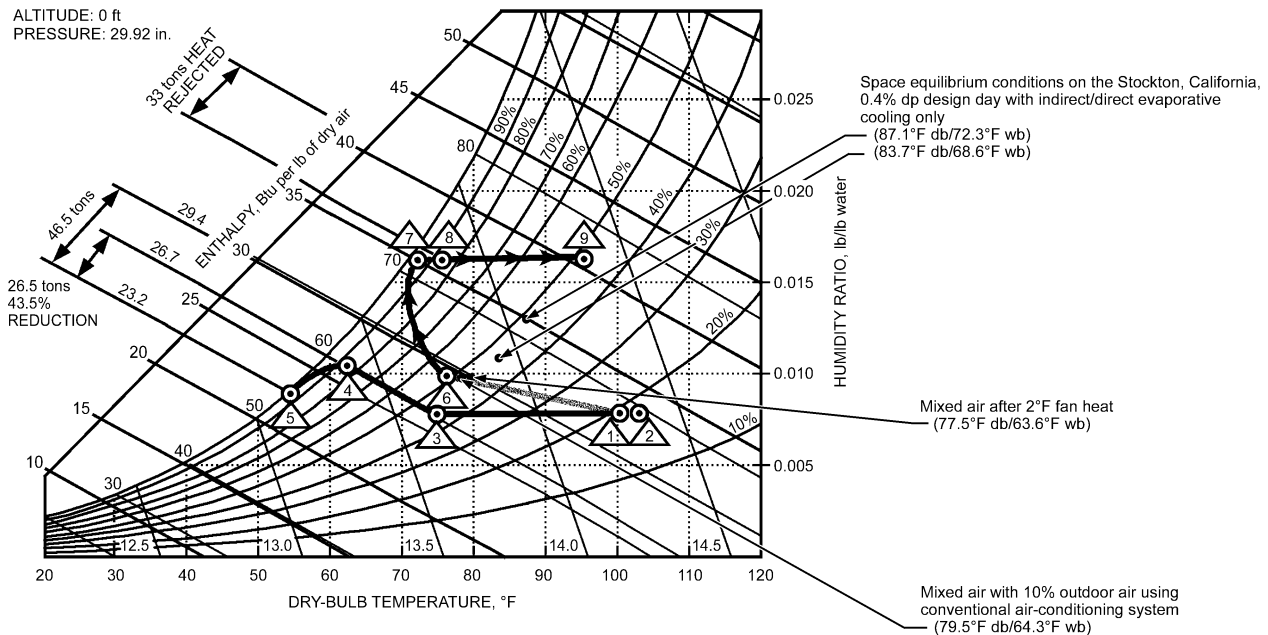
PSYCHROMETRIC STATE POINTS:

1. 100°F db/69°F wb	3. 74°F db/60.4°F wb	5. 55°F db/55°F wb	7. 72.8°F db/72.5°F wb	9. 95°F db/78.4°F wb
2. 103°F db/69.9°F wb	4. 61.7°F db/60.4°F wb	6. 75°F db/63°F wb	8. 75°F db/73.1°F wb	

Fig. 12   Psychrometrics of 100% OA, Two-Stage Evaporative Cooling Design (20,000 cfm Supply, 18,000 cfm Return) Compared with 10% OA Conventional System Operating at Stockton, California, ASHRAE 0.4% db Design Condition
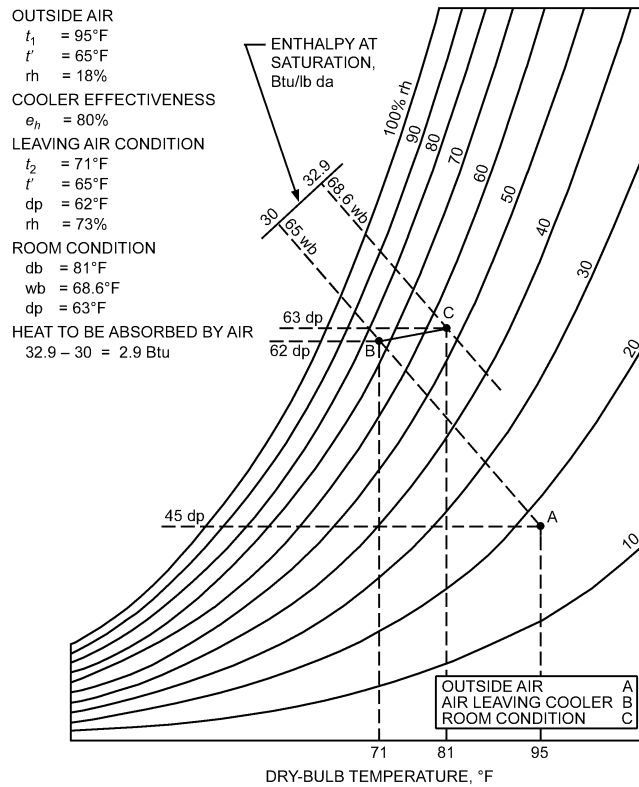
Fig. 13 Psychrometric Diagram for Example 1

airflow depends on a direct evaporative cooler effectiveness of 70 to 80%. Obviously, the method must be modified for unusual conditions such as large unshaded glass areas, uninsulated roof exposure, or high internal heat gain. Also, such empirical methods make no attempt to predict air temperature at specific points; they merely establish an air quantity for use in sizing equipment.

Example 1. An indirect evaporative cooler is to be installed in a 50 by 80 ft one-story office building with a 10 ft ceiling and a flat roof. Outside design conditions are assumed to be 95°F db and 65°F wb. The following heat gains are to be used in the design:

	Heat Gains, Btu/h
All walls, doors, and roof	78,500
Glass area	5,960
Occupants (sensible load)	17,000
Lighting	62,700
Total sensible heat load	164,160
Total latent load (occupants)	21,250
Total heat load	185,410

Find the required air quantity, the temperature and humidity ratio of the air leaving the cooler (entering the office), and the temperature and humidity ratio of the air leaving the office.

Solution: A temperature rise of 10°F in the cooling air is assumed. The airflow rate that must be supplied by the indirect evaporative cooler may be found from the following equation:

$$Q_{ra} = \frac{q_s}{60 \rho c_p (t_1 - t_s)} = \frac{164,160}{60 \times 0.018 \times 10} = 15,200 \text{ cfm} \qquad (1)$$

where

Q_{ra} = required airflow, cfm
q_s = instantaneous sensible heat load, Btu/h

t_1 = inside air dry-bulb temperature, °F
t_s = room supply air dry-bulb temperature, °F
ρc_p = density times specific heat of air ≈ 0.018 Btu/ft³·°F

This air volume represents a 2.6 min $(50 \times 80 \times 10/15,200)$ air change for a building of this size. The indirect evaporative air cooler is assumed to have a saturation effectiveness of 80%. This is the ratio of the reduction of the dry-bulb temperature to the wet-bulb depression of the entering air. The dry-bulb temperature of the air leaving the indirect evaporative cooler is found from the following equation:

$$t_2 = t_1 - \frac{e_h}{100}(t_1 - t') = 95 - \frac{80}{100}(95 - 65) = 71°F \qquad (2)$$

where

t_2 = dry-bulb temperature of leaving air, °F
t_1 = dry-bulb temperature of entering air, °F
e_h = humidifying or saturating effectiveness, %
t' = thermodynamic wet-bulb temperature of entering air, °F

From the psychrometric chart, the humidity ratio W_2 of the cooler discharge air is 0.01185 lb/lb_da. The humidity ratio W_3 of the air leaving the space being cooled is found from the following equation:

$$W_3 = \frac{q_e}{4840 Q_{ra}} + W_2 \qquad (3)$$

$$W_3 = \frac{21250}{4840 \times 15200} + 0.01185 = 0.01214 \text{ lb/lb (dry air)}$$

where q_e = latent heat load in Btu/h.

The remaining values of wet-bulb temperature and relative humidity for the problem may be found from the psychrometric chart. Figure 13 illustrates the various relationships of outside air, supply air to the space, and discharge air.

The wet-bulb depression (WBD) method to estimate airflow gives the following result:

$$\text{WBD}/10 = (95 - 65)/10 = 3.0 \text{ min per air change}$$

$$Q_{ra} = \frac{\text{volume}}{\text{air change rate}} = \frac{80 \times 50 \times 10}{3.0} = 13,300 \text{ cfm}$$

Although not exactly alike, these two air volume calculations are close enough to select cooler equipment of the same size.

EXHAUST REQUIRED

If air is not exhausted freely, the increased static pressure will reduce airflow through the evaporative cooler. The result is a marked increase in the moisture and heat absorbed per unit mass of air leaving the evaporative cooler. Reduced airflow also reduces the air velocity in the room. The combination of these effects reduces the comfort level. Properly designed systems should have a minimum of 2 ft² of exhaust area for every 1000 cfm. If the exhaust area is not sufficient, a powered exhaust should be used. The amount of power depends on the total airflow and the amount of free or gravity exhaust. Some applications require that the powered exhaust capacity equal the cooler output.

TWO-STAGE COOLING

Two-stage coolers for commercial applications can extend the range of atmospheric conditions under which comfort requirements can be met, as well as reduce the energy cost. For the same design conditions, two-stage cooling provides lower cool-air temperatures, which reduces required airflow.

INDUSTRIAL APPLICATIONS

In factories with large internal heat loads, it is difficult to approach outside conditions during the summer simply by ventilating without using extremely large quantities of outside air. Both direct and indirect evaporative cooling may be used to reduce heat
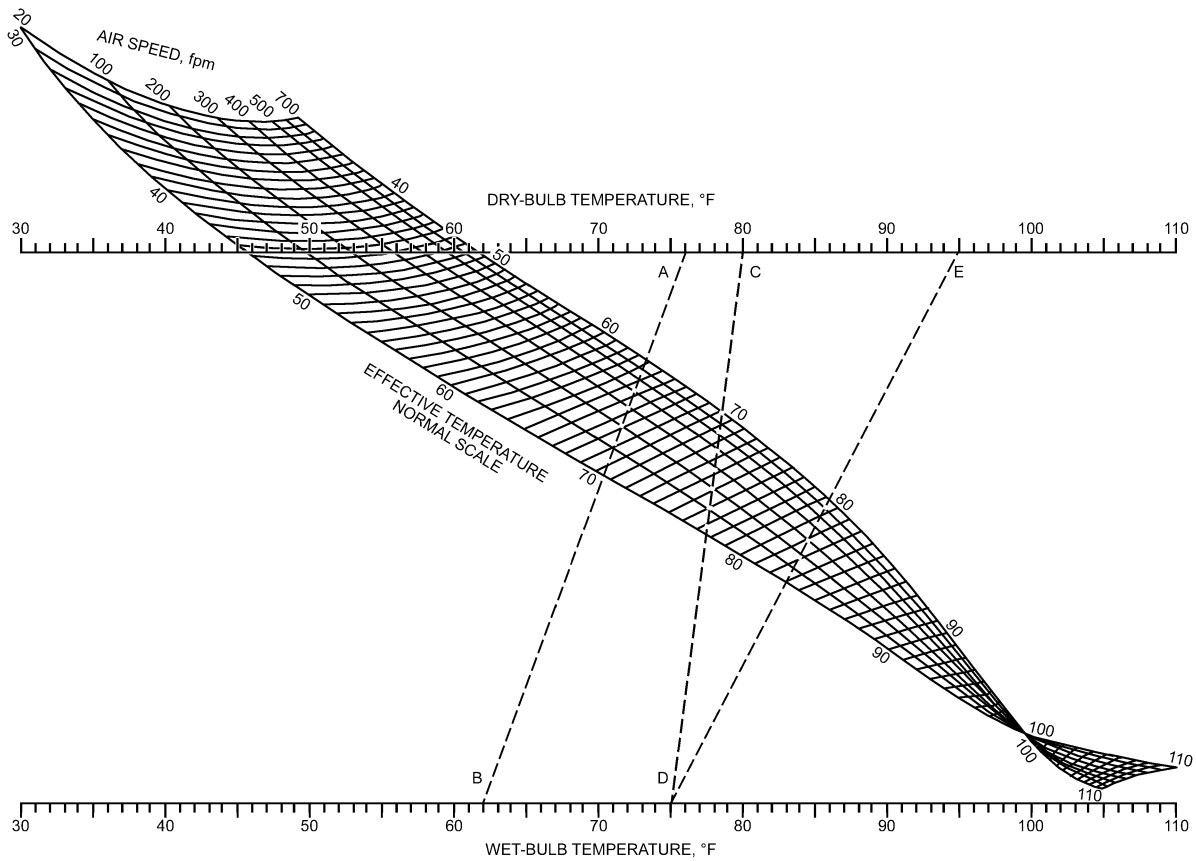
Fig. 14   Effective Temperature Chart

stress with less outside air. Evaporative cooling normally results in lower effective temperatures than ventilation alone, regardless of the ambient relative humidity.

Effective Temperature. Comfort cooling in air-conditioned spaces is usually based on providing space temperature and relative humidity conditions for human comfort without a draft. The effective temperature relates the cooling effects of air motion and relative humidity to the effect of conditioned (cooled) air. Figure 14 shows an effective temperature chart for air velocities from 20 to 700 fpm. Although the maximum velocity shown on the chart is 700 fpm, workers exposed to high-heat-producing operations may prefer air movement up to 4000 fpm to offset the radiant heat effect of equipment. Because the normal working range of the chart is approximately midway between the vertical dry- and wet-bulb scales, changes in either dry- or wet-bulb temperatures have similar effects on worker comfort. A reduction in either one decreases the effective temperature by about one-half of the reduction. Lines ED and CD on the chart illustrate this.

A condition of 95°F db and 75°F wb was chosen as the original state, because this condition is usually considered the summer design criterion in most areas. Reducing the temperature 15°F by evaporating water adiabatically provides an effective temperature reduction of 5.5°F for air moving at 20 fpm and a reduction of 9.5°F for air moving at 700 fpm, an improvement of 4°F.

The reduction in dry-bulb temperature through water evaporation increases the effectiveness of the cooling power of moving air in this example by 137%. On Line ED, the effective temperature varies from 83°F at 20 fpm to 79.5°F at 700 fpm with unconditioned air, whereas Line CD indicates an effective temperature of 77.5°F at 20 fpm and 70°F at 700 fpm with air cooled by a simple direct evaporative process. In the unconditioned case, increasing the air velocity from 20 to 700 fpm resulted in only a 3.5°F decrease in effective

temperature. This contrasts with a 7.5°F decrease in effective temperature for the same range of air movement when the dry-bulb temperature was lowered by water evaporation. This demonstrates that direct evaporative cooling can provide a more comfortable environment regardless of geographical location.

Two methods are demonstrated to illustrate the environmental improvement that may be achieved with evaporative coolers. In one method, shown in Figure 15, temperature is plotted against time of day to illustrate effective temperature depression over time. Curve A shows ambient maximum dry-bulb temperature recordings. Curve B shows the corresponding wet-bulb temperatures. Curve C depicts the effective temperature when unconditioned air is moved over a person at 300 fpm. Curve D illustrates air conditioned in an 80% effective direct evaporative cooler before being projected over the person at 300 fpm. Curve E shows the additional decrease in effective temperature with air velocities of 700 fpm. Although a maximum suggested effective temperature of 80°F is briefly exceeded with unconditioned air at 300 fpm (Curve C), both the differential and total hours are substantially reduced from still air conditions. Curves D and E illustrate that, in spite of the high wet-bulb temperatures, the in-plant environment can be continuously maintained below the suggested upper limit of 80°F effective temperature. This demonstration assumes that the combination of air velocity, duct length, and insulation between the evaporative cooler and the duct outlet is such that there is little heat transfer between air in the ducts and warmer air under the roof.

Figure 16 illustrates another method of demonstrating the effect of using direct evaporative coolers by plotting effective comfort zones using ambient wet- and dry-bulb temperatures on a psychrometric chart (Crow 1972). The dashed lines show the improvement to expect when using an 80% effective direct evaporative cooler.
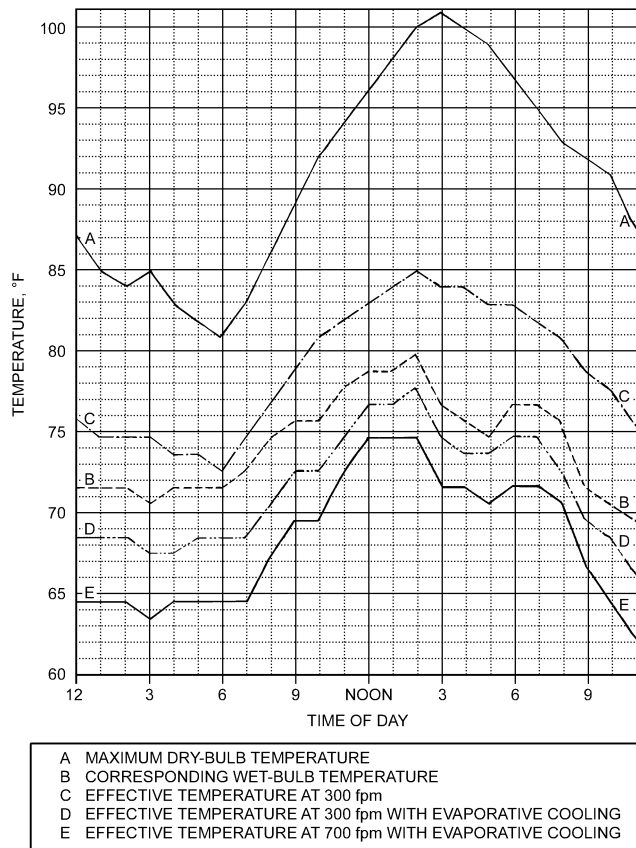
Fig. 15   Effective Temperature for Summer Day in Kansas City, Missouri (Worst-Case Basis)

Area Cooling

Both direct and indirect evaporative cooling may be used for area or spot cooling of industrial buildings. Both can be controlled either automatically or manually. In addition, evaporative coolers can supply tempered air during fall, winter, and spring. Gravity or power ventilators exhaust the air. Area cooling works well in buildings where personnel move about and workers are not subjected to concentrated, radiant heat sources. Area cooling may be used in either high- or low-bay industrial buildings, but may provide significant advantages in high-bay construction where cooling loads associated with roofs, lighting, and heat from equipment may be effectively eliminated by taking advantage of stratification. When cooling an area, ductwork should be designed to distribute air to the lower 10 ft of the space to ensure that cooler air is supplied to the workers.

Cooling requirements change from day to day and season to season, so, if discharge grilles are used, they should be adjustable to prevent drafts. The horizontal blades of an adjustable grille can be adjusted so that air is discharged above workers' heads rather than directly on them. In some cases, the air volume can be adjusted, either at each outlet or for the entire system, in which case the exhaust volume may need to be varied accordingly.

Spot Cooling

Spot cooling is a more efficient use of equipment when personnel work in one spot. Cool air is brought to the spot at levels below 10 ft, and may even be delivered from floor outlets. Selection of the duct height may depend on the location of other equipment in the area. For best results, air velocity should be kept low. Controls may be automatic or manual, with the fan often operating throughout the year. Workers are especially appreciative of spot cooling in
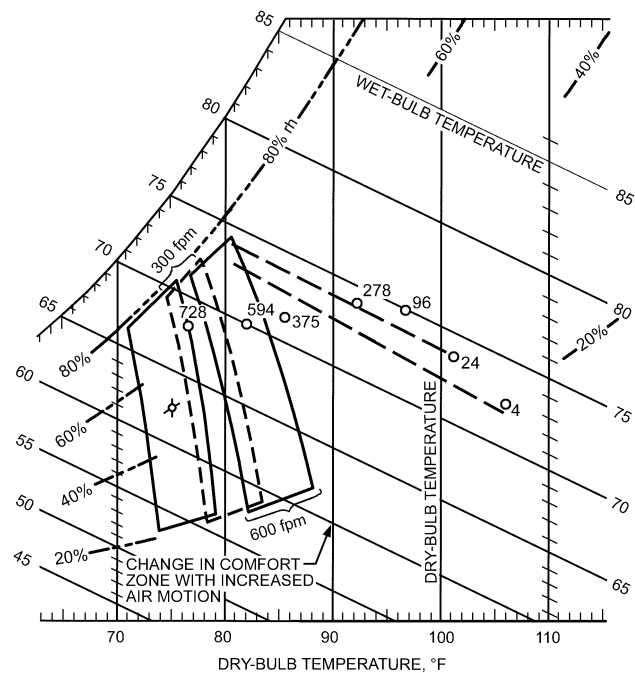
Fig. 16   Change in Human Comfort Zone as Air Movement Increases

hot environments, such as in chemical plants and die casting shops, and near glass-forming machines, billet furnaces, and pig and ingot casting.

When spot-cooling a worker, the air volume depends on the throw of the air jet, activity of the worker, and amount of heat that must be overcome. Air volumes can vary from 200 to 5000 cfm per worker, with target velocities ranging between 200 to 4000 fpm. The outlets should be between 4 to 10 ft from workstations to avoid entrainment of warm air and to effectively blanket workers with cooler air. Provisions should be made for workers to control the direction of air discharge, because air motion that is appropriate for hot weather may be too great for cool weather or even cool mornings. Volume controls may be required to prevent overcooling the building and to minimize excessive grille blade adjustment.

Spot cooling is useful in rooms with elevated temperatures, regardless of climatic or geographical location. When the dry-bulb temperature of the air is below skin temperature, convection rather than evaporation cools workers. In these conditions, an 80°F airstream can provide comfort regardless of its relative humidity.

Cooling Large Motors

Electrical generators and motors are generally rated for a maximum ambient temperature of 104°F. When this temperature is exceeded, excessive temperatures develop in the electrical windings unless the load on the motor or generator is reduced. By providing evaporatively cooled air to the windings, this equipment may be safely operated without reducing the load. Likewise, transformer capacity can be increased using evaporative cooling.

The heat emitted by high-capacity electrical equipment may also be sufficient to raise the ambient condition to an uncomfortable level. With mill drive motors, an additional problem is often encountered with the commutator. If the air used to ventilate the motor is dry, the temperature rise through the motor results in a still lower relative humidity, at which the brush film can be destroyed, with unusual brush and commutator wear as well as the occurrence of dusting.

As a rule, a motor having a temperature rise of 25°F requires approximately 120 cfm of ventilating air per kilowatt hour of loss. If the inlet air to the motor is 95°F, the air leaving the motor would be
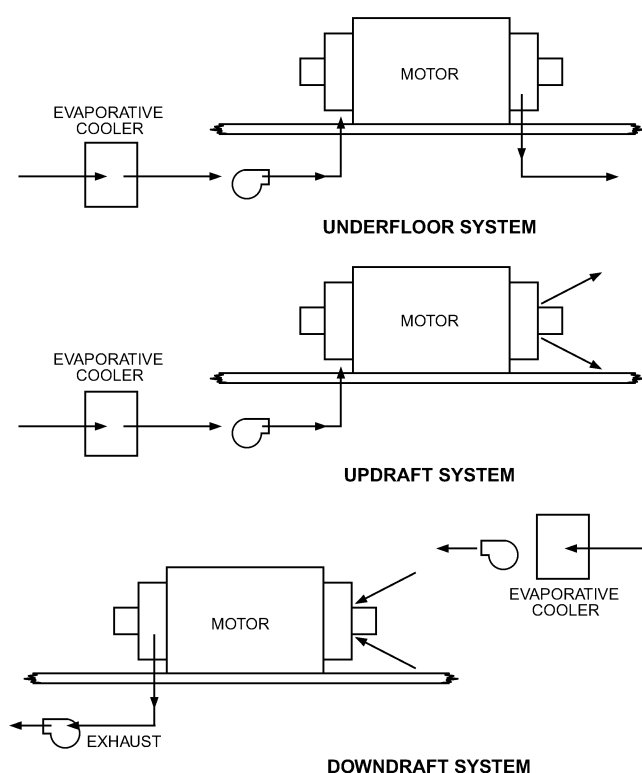
Fig. 17 Arrangements for Cooling Large Motors

120°F. This average motor temperature of over 107°F is 3°F higher than it should be for the normal 104°F ambient. The same quantity of 95°F db inlet air at 75°F wb can be cooled by a direct evaporative cooler with a 97% saturation effectiveness. The resulting 88°F average motor temperature would eliminate the need for special high-temperature insulation and improve the ability of the motor to absorb temporary overloads. By comparison, an air quantity of 185 cfm would be required if supplied by a cooler with 80% saturation effectiveness.

Figure 17 shows three basic arrangements for motor cooling. The air from the evaporative cooler may be directed on the motor windings, or into the room, which requires an increased air volume to compensate for the building heat load. Operation of a direct evaporative cooler should be keyed to motor operation to ensure that (1) saturated or nearly saturated air is never introduced into a motor until it has had time to warm up, and (2) if more than one motor is served by a single system, air circulation through idle motors should be prevented.

Cooling Gas Turbine Engines and Generators

Combustion turbines used for electric power production are normally rated at 59°F. Their performance is greatly influenced by the compressor inlet air temperature because temperature affects air density and therefore mass flow. As ambient temperature increases, demand on electric utilities increases and the capacity of the combustion turbine decreases. Recovery of capacity because of inlet air cooling is approximately 0.4%/°F (cooling). Direct and indirect evaporative cooling is beneficial to gas turbine performance in almost all climates because when the air is the hottest, it generally has the lowest relative humidity. Expected increases in output using direct evaporative cooling range from 5.8% in Albany, New York, to 14% in Yuma, Arizona. In addition to increasing gas turbine output, direct evaporative cooling also improves heat rate and reduces NO_x emissions.

For an installation of this type, the following precautions must be taken: (1) mist eliminators must be provided to stop entrainment of free moisture droplets, (2) coolers must be turned off at a temperature below 45°F to prevent icing, and (3) water quality must be monitored closely (Stewart 1999).

Process Cooling

In the manufacture of textiles and tobacco and in processes such as spray coating, the required accurate relative humidity control can be provided by direct evaporative coolers. For example, textile manufacturing requires relatively high humidity and the machinery load is heavy, so a split system is customarily used whereby free moisture is introduced directly into the room. The air handled is reduced to approximately 60% of that normally required by an all-outside-air, direct evaporative cooler.

Cooling Laundries

Laundries have one of the most severe environments in which direct evaporative air cooling is applied because heat is produced not only by the processing equipment, but by steam and water vapor as well. A properly designed direct evaporative cooler reduces the temperature in a laundry 5 to 10°F below the outside temperature. With only fan ventilation, laundries usually exceed the outside temperature by at least 10°F. Air distribution should be designed for a maximum throw of not more than 30 ft. A minimum circulated velocity of 100 to 200 fpm should prevail in the occupied space. Ducts can be located to discharge the air directly onto workers in exceptionally hot areas, such as pressing and ironing departments. For these outlets, there should be some means of manual control to direct the air where it is desired, with at least 500 to 1000 cfm at a target velocity of 600 to 900 fpm for each workstation.

Cooling Wood and Paper Products Facilities

Wood-processing plants and paper mills are good applications for evaporative cooling because of the high temperatures and gases associated with wood-processing equipment. Wood dust should be kept out of the recirculation sumps of evaporative coolers, because the dust contains microorganisms and worm larvae that will grow in sumps.

Because of the types of gases and particulates present in most paper plants, water-cooled systems are preferred over air-cooled systems. The most prevalent contaminant is wood dust. Chlorine gas, caustic soda, sulfur, hydrogen sulfide, and other compounds are also serious problems, because they accelerate the corrosion of steel and yellow metals. With more efficient air scrubbing, ambient air quality in and about paper mills has become less corrosive, allowing the use of equipment with well-analyzed and properly applied coatings on coils and housings. Phosphor-free brazed coil joints should be used in areas where sulfur compounds are present.

Heat is readily available from processing operations and should be used whenever possible. Most plants have good-quality hot water and steam, which can be readily geared to unit heater, central station, or reheat use. Newer plant air-conditioning methods, including evaporative cooling, that use energy-conservation techniques (such as temperature stratification) lend themselves to this type of large structure. Chapter 24 has further information on air-conditioning of paper facilities.

OTHER APPLICATIONS

Cooling Power-Generating Facilities

An appropriate air-cooling system can be selected once preliminary heating and cooling loads are determined and criteria are established for temperature, humidity, pressure, and airflow control. The same considerations for selection apply to power-generating facilities and industrial facilities.

Cooling Mines

Chapter 27 describes evaporative cooling methods for mines.

Cooling Animals

The design criteria for farm animal environments and the need for cooling animal shelters are discussed in Chapter 22. Direct evaporative cooling is ideally suited to farm animal shelters because 100% outside air is used. Fresh air removes odors and reduces the harmful effects of ammonia fumes. At night and in the spring and fall, direct evaporative cooling can also be used for ventilation.

Equipment should be sized to change the air in the shelter in 1 to 2 min, assuming the ceiling height does not exceed 10 ft. This flow rate will usually keep the shelter at or below 80°F. In addition, conditions can be improved with portable or packaged spot coolers.

For poultry housing, most applications require an air change every 0.75 to 1.5 min, with the majority at 1 min. Placing the fans at the ends or the center of the house, with the direct evaporative cooler located at the opposite end, creates a tunnel ventilation system with an air velocity of 300 to 500 fpm. Fans are generally selected for a total pressure drop of 0.125 in. of water, which means that the direct evaporative cooling media cannot have a pressure drop in excess of 0.075 in. of water. Thus, to prevent an inadequate volume of air being pulled through the poultry house, the designer must carefully size the media selected.

Using direct evaporative cooling for poultry broiler houses decreases bird mortality, improves feed conversion ratio, and increases the growth rate. Poultry breeder houses are evaporatively cooled to improve egg production and fertility during warm weather. Evaporative cooling of egg layers improves feed conversion, shell quality, and egg size. When the ambient outside temperature exceeds 100°F, evaporative cooling is often the only way to keep a flock alive. Direct evaporative cooling is also used to cool swine farrowing and gestation houses to improve production.

Produce Storage Cooling

Potatoes. Direct evaporative cooling for bulk potato storage should pass air directly through the pile. The ventilation and cooling system should provide 1.0 to 1.5 cfm/100 lb of potatoes. Average potato density is 45 lb/ft^3 in the pile. Pile depths range from 12 to 20 ft, which creates a static pressure of 0.15 to 0.25 in. of water. Ventilation consists of fresh air inlets, return air openings, exhaust air openings, main air ducts, and lateral ducts with holes or slots to distribute air uniformly through the pile. Distribution ducts should be placed no farther apart than 80% of the potato pile depth, and should extend to within 18 in. of the storage walls. Ducts, the direct evaporative cooling media, and any refrigeration coils cause a static pressure ranging from 0.5 to 1.0 in. of water. Typically the total static pressure ranges from 0.75 to 1.25 in. of water, depending on the equipment. Air speed through each of the openings in the ventilation/cooling system should be as listed in Table 4.

Direct evaporative cooling media should be 90 to 95% effective, depending on the climate. In arid regions, 95% effective media are recommended. In more humid climates, such as in the midwestern and eastern United States, 90% effective media are commonly used. Air speed through the media should be 500 to 550 fpm to ensure high pad efficiency with low static-pressure penalty.

Table 4   Air Speeds for Potato Storage Evaporative Cooler

Opening	Minimum Speed, fpm	Maximum Speed, fpm	Desired Speed, fpm
Fresh air inlet	1000	1400	1200
Return air opening	1000	1400	1200
Exhaust opening	1000	1200	1100
Main duct	500	900	700
Lateral duct	750	1100	900
Slot	900	1300	1050

For more information, see Chapter 24 of the 2006 *ASHRAE Handbook—Refrigeration*

Apples. Direct evaporative cooling for apple storage without refrigeration should distribute cool air to all parts of the storage. The evaporative cooler may be floor-mounted or located near the ceiling in a fan room. Air should be discharged horizontally at ceiling level. Because the prevailing wet-bulb temperature limits the degree of cooling, a cooler with maximum reasonable size should be installed to reduce the storage temperature rapidly and as close to the wet-bulb temperature as possible. Generally, a cooler designed to exchange air every 3 min (20 air changes per hour) is the largest that can be installed. This capacity provides a complete air change every 1 to 1.5 min (40 to 60 air changes per hour) when the storage is loaded.

For further information on apple storage, see Chapter 22 of the 2006 *ASHRAE Handbook—Refrigeration*.

Citrus. The chief purpose of evaporative cooling as applied to fruits and vegetables is to provide an effective, inexpensive means of improving storage. However, it also serves a special function in the case of oranges, grapefruit, and lemons. Although mature and ready for harvest, citrus fruits are often still green. Color change (degreening) is achieved through a sweating process in rooms equipped with direct evaporative cooling. Air with a high relative humidity and a moderate temperature is circulated continuously during the operation. Ethylene gas, the concentration depending on the variety and intensity of green pigment in the rind, is discharged

Table 5   Three-Year Average Solar Radiation for Horizontal Surface During Peak Summer Month

City	Btu/h·ft^2	City	Btu/h·ft^2
Albuquerque, NM	198	Lemont, IL	142
Apalachicola, FL	170	Lexington, KY	170
Astoria, OR	132	Lincoln, NE	150
Atlanta, GA	158	Little Rock, AR	148
Bismarck, ND	140	Los Angeles, CA	162
Blue Hill, MA	128	Madison, WI	138
Boise, ID	155	Medford, OR	170
Boston, MA	125	Miami, FL	153
Brownsville, TX	175	Midland, TX	177
Caribou, ME	115	Nashville, TN	154
Charleston, SC	152	Newport, RI	138
Cleveland, OH	152	New York, NY	140
Columbia, MO	153	Oak Ridge, TN	148
Columbus, OH	127	Oklahoma City, OK	165
Davis, CA	184	Phoenix, AZ	200
Dodge City, KS	184	Portland, ME	133
East Lansing, MI	132	Prosser, WA	176
East Wareham, MA	132	Rapid City, SD	152
El Paso, TX	195	Richland, WA	137
Ely, NV	175	Riverside, CA	176
Fort Worth, TX	176	St. Cloud, MN	132
Fresno, CA	188	San Antonio, TX	176
Gainesville, FL	156	Santa Maria, CA	188
Glasgow, MT	152	Sault Ste. Marie, MI	138
Grandby, CO	149	Sayville, NY	148
Grand Junction, CO	173	Schenectady, NY	117
Great Falls, MT	150	Seabrook, NJ	135
Greensboro, NC	155	Seattle, WA	117
Griffin, GA	164	Spokane, WA	139
Hatteras, NC	177	State College, PA	141
Indianapolis, IN	140	Stillwater, OK	167
Inyokern, CA	218	Tallahassee, FL	134
Ithaca, NY	145	Tampa, FL	167
Lake Charles, LA	160	Upton, NY	148
Lander, WY	177	Washington, D.C.	142
Las Vegas, NV	195		

into the rooms. Ethylene destroys the chlorophyll in the rind, allowing the yellow or orange color to become evident. During degreening, a temperature of 70°F and a relative humidity of 88 to 90% are maintained in the sweat room. (In the Gulf States, 82 to 85°F with 90 to 92% rh is used.) The evaporative cooler is designed to deliver 11 cfm per pound of fruit.

Direct and indirect evaporative cooling is also used as a supplement to refrigeration in the storage of citrus fruit. Citrus storage requires refrigeration in the summer, but the required conditions can often be obtained using evaporative cooling during the fall, winter, and spring when the outside wet-bulb temperature is low. For further information, see Chapter 23 of the 2006 *ASHRAE Handbook—Refrigeration.*

Cooling Greenhouses

Proper regulation of greenhouse temperatures during the summer is essential for developing high-quality crops. The principal load on a greenhouse is solar radiation, which at sea level at about noon in the temperate zone is approximately 200 Btu/h·ft^2. Smoke, dust, or heavy clouds reduce the radiation load. Table 5 gives solar radiation loads for representative cities in the United States. Note that the values cited are average solar heat gains, not peak loads. Temporary rises in temperature inside a greenhouse can be tolerated; an occasional rise above design conditions is not likely to cause damage.

Not all solar radiation that reaches the inside of the greenhouse becomes a cooling load. About 2% of the total solar radiation is used in photosynthesis. Transpiration of moisture varies by crop, but typically uses about 48% of the solar radiation. This leaves 50% to be removed by the cooler. Example 2 shows a method for calculating the size of a greenhouse evaporative cooling system.

Example 2. A direct evaporative cooler is to be installed in a 50 by 100 ft greenhouse. Design conditions are assumed to be 92°F db and 73°F wb, and average solar radiation is 138 Btu/h·ft^2. An inside temperature of 90°F db must not be exceeded at design conditions.

Solution: The direct evaporative air cooler is assumed to have a saturation effectiveness of 80%. Equation (2) may be used to determine the dry-bulb temperature of the air leaving the direct evaporative cooler:

$$t_2 = 92 - \frac{80}{100}(92 - 73) = 77°F$$

The following equation, a modification of Equation (1), may be used to calculate the airflow rate that must be supplied by the direct evaporative cooler:

$$Q_{ra} = \frac{0.5AI_t}{\rho c_p(t_1 - t_2)} \qquad (4)$$

where

A = greenhouse floor area, ft^2
I_t = total incident solar radiation, Btu/h·ft^2 of receiving surface
$60\rho c_p$ = density times specific heat of air times 60 min/h ≈ 1.0 Btu/ft^3·°F at design conditions

For this problem

$$Q_{ra} = \frac{0.5 \times 50 \times 100 \times 138}{1.0(90 - 77)} = 26,500 \text{ cfm}$$

Horizontal illumination from the direct rays of noonday summer sun with clear sky can be as much as 10,000 footcandles (fc); under clear glass, this is approximately 8500 fc. Crops such as chrysanthemums and carnations grow best in full sun, but many foliage plants, such as gloxinias and orchids, do not need more than 1500 to 2000 fc. Solar radiation is nearly proportional to light intensity. Thus, the greater the amount of shade, the smaller the cooling capacity required. A value of 100 fc is approximately equivalent to 3 Btu/h·ft^2. Although atmospheric conditions such as clouds and haze affect the relationship, this is a safe conversion factor. This relationship should be used instead of Table 5 when illumination can be determined by design or measurement.

Direct evaporative cooling for greenhouses may be under either positive or negative pressure. Regardless of the type of system used, the length of air travel should not exceed 160 ft. The temperature rise of the cool air limits the throw to this value. Air movement must be kept low because of possible mechanical damage to the plants, but it should generally not be less than 100 fpm in areas occupied by workers.

ECONOMIC FACTORS

Design of direct and indirect evaporative cooling systems and sizing of equipment is based on the load requirements of the application and on the local dry- and wet-bulb design conditions, which may be found in Chapter 28 of the 2005 *ASHRAE Handbook—Fundamentals.* Total energy use for a specific application during a set period may be forecasted by using annual weather data. Dry-bulb and mean coincident wet-bulb temperatures, with the hours of occurrence, can be summarized and used in a modified bin procedure. The calculations must reflect the hours of use, conditions of load, and occupancy. Because of annual variations in dry and wet-bulb temperatures, and the effect of increasing cooling capacity with decreasing wet-bulb temperatures, bin calculations using mean coincident wet-bulb temperatures generally produce conservative results. When comparing various cooling systems, cost analysis should include annual energy reduction at the applicable electrical rate, plus anticipated energy cost escalation over the expected life.

Many areas have time-of-day electrical metering as an incentive to use energy during off-peak hours when rates are lowest. Reducing air-conditioning kilowatt demand is especially important in areas with ratcheted demand rates (Scofield and DesChamps 1980). Thermal storage using ice banks or chilled-water storage may be used as part of a multistage evaporatively refrigerated cooler to combine the energy-saving advantages of evaporative cooling and off-peak savings of thermal storage (Eskra 1980).

Direct Evaporation Energy Saving

Direct evaporative cooling may be used in all climates to save cooling and humidification energy. In humid climates, the benefits of direct evaporation are realized during periods when outside air is warm and dry, but cooling savings are unlikely to be realized during peak design conditions. In more arid areas, direct evaporative cooling may partially or fully offset mechanical cooling at peak load conditions. Humidification energy savings may be realized during the heating season when outside air is used to provide cooling and humidification. If properly controlled, direct evaporative cooling can use waste heat otherwise rejected from buildings when outside air is used for cooling.

Indirect Evaporation Energy Saving

Indirect evaporative cooling may be used in all climates to save cooling and, in some applications, heating energy. In humid climates, indirect evaporative cooling may be used throughout the cooling cycle to precool outside air. Indirect evaporative cooling can be used to extend the range of 100% outside air ventilation to both higher and lower temperatures, and to increase the percentage of outside air a system can support at any given temperature through heat recovery. In high-humidity areas, indirect evaporative cooling may be used to (1) partially offset mechanical cooling requirements at peak load conditions and (2) provide better control over low-load humidity conditions by permitting the use of smaller refrigeration equipment to provide ventilation over a wider range of outside air conditions. The cost of heating may be reduced when operating below temperatures at which minimum outside air quantities exceed the rates of ventilation required for free cooling by using heat recovered from building exhausts.

Water Cost for Evaporative Cooling

Typically, domestic service water is used for evaporative cooling to avoid excessive scaling and associated problems with poor water quality. In designing evaporative coolers, the cost of water treatment is included in the overall project cost. However, water cost is typically ignored for evaporative coolers because it is usually an insignificant part of the operational cost. Depending on the ambient dry-bulb temperature and wet-bulb depression for a specific location, the cost of water could become a significant part of the operational cost, because the greater the differential between dry- and wet-bulb temperatures, the greater the amount of water evaporated (Mathur 1997, 1998).

PSYCHROMETRICS

Figure 18 shows the two-stage (indirect/direct) process applied to nine cities in the western United States. The examples indicated are primarily shown for arid areas, but the principles also apply to moderately humid and humid areas when weather conditions permit. For each city indicated, the entering conditions to the first-stage indirect unit are at or near the 0.4% design dry- and wet-bulb temperatures in Chapter 28 of the 2005 *ASHRAE Handbook—Fundamentals*. Although higher effectiveness can be achieved for both the indirect and direct evaporative processes modeled, the effectiveness ratings are 60% for the first (indirect) stage and 90% for the second (direct) stage. Leaving air temperatures range from 52 to 70°F, with leaving conditions approaching saturation.

Figure 18 projects space conditions in each city at 78°F db for these second-stage supply temperatures based on a 95% room sensible heat factor (i.e., room sensible heat/room total heat). Except in Wichita, Los Angeles, and Seattle, room conditions can be maintained in the comfort zone without a refrigerated third stage. But even in these cities, third-stage refrigeration requirements are sharply reduced as compared to conventional mechanical cooling. However, Figures 18 and 19 indicate the need to consider the following factors when deciding whether to include a third cooling stage:

- As the room sensible heat factor decreases, the supply air temperature required to maintain a given room condition decreases.
- As supply air temperature increases, the supply air quantity must increase to maintain space temperature, which results in higher air-side initial cost and increased supply air fan power.
- A decrease in the required room dry-bulb temperature requires an increase in the supply air quantity. For a given room sensible heat factor, a decrease in room dry-bulb temperature may cause the relative humidity to exceed the comfort zone.
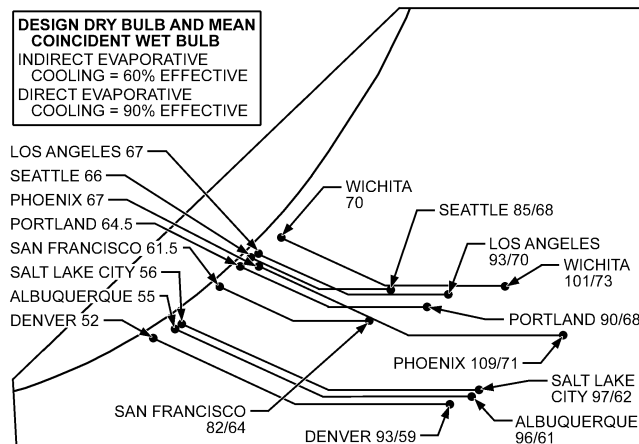
- The suggested 0.4% entering design (dry-bulb/mean wet-bulb) conditions are only one concern. Partial-load conditions must also be considered, along with the effect (extent and duration) of spike wet-bulb temperatures. Mean wet-bulb temperatures can be used to determine energy use of the indirect/direct system. However, the higher wet-bulb temperature spikes should be considered to determine their effect on room temperatures.

An ideal condition for maximum use with minimum energy consumption of a two- and three-stage indirect/direct system is a room sensible heat factor of 90% and higher, a supply air temperature of 60°F, and a dry-bulb room design temperature of 78°F. In many cases, third-stage refrigeration is required to ensure satisfactory dry-bulb temperature and relative humidity. Example 3 shows a method for determining the refrigeration capacity for three-stage cooling. Figure 20 is a psychrometric diagram of the process.

Example 3. Assume the following:
- Supply air quantity = 24,000 cfm; supply air temperature = 60°F
- Design condition = 99°F db and 68°F wb
- Effectiveness of indirect unit = 60%;
- Effectiveness of direct unit = 90%

Using Equation (2), the leaving air state from the indirect unit (first stage) is

$$99 - 0.60(99 - 68) = 80.4°F \text{ db } (61.8°F \text{ wb})$$

Using Equation (2), the leaving air state from the direct unit (second stage) is

$$80.4 - 0.90(80.4 - 61.8) = 63.7°F \text{ db } (61.8°F \text{ wb})$$

Calculate booster refrigeration capacity to drop the supply air temperature from 63.7°F to the required 60°F.

If the refrigerating coil is located ahead of the direct unit,

$$\text{Btu/h cooling} = \frac{60(h_1 - h_2)(\text{supply air, cfm})}{\text{Specific volume dry air at leaving air condition}}$$

With numeric values of enthalpies h_1 and h_2 (in Btu/lb) and the specific volume of air (in $\text{ft}^3/\text{lb}_{da}$) taken from ASHRAE Psychrometric Chart No. 1, the cooling load is calculated as follows:

$$60(27.6 - 25.5)24,000/13.78 = 219,400 \text{ Btu/h} = 18.3 \text{ tons}$$

The load for a coil located in the leaving air of the direct unit is

$$60(27.6 - 25.5)24,000/13.43 = 225,000 \text{ Btu/h} = 18.8 \text{ tons}$$

Depending on the location of the booster coil, the preceding calculations can be used to determine third-stage refrigeration capacity and to select a cooling coil.

Fig. 18 Two-Stage Evaporative Cooling at 0.4% Design Condition in Various Cities in Western United States
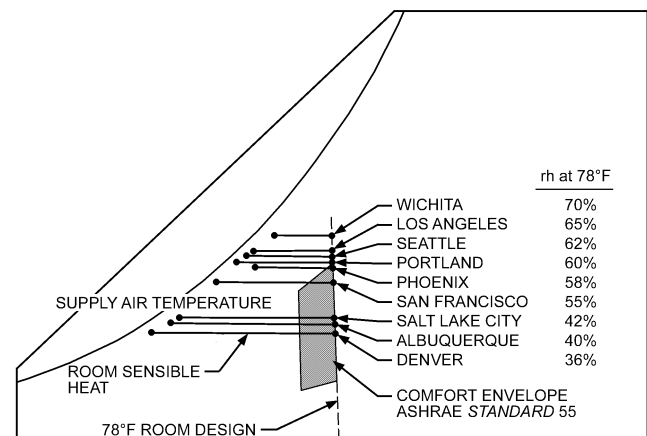
Fig. 19   Final Room Design Conditions After Two-Stage Evaporative Cooling
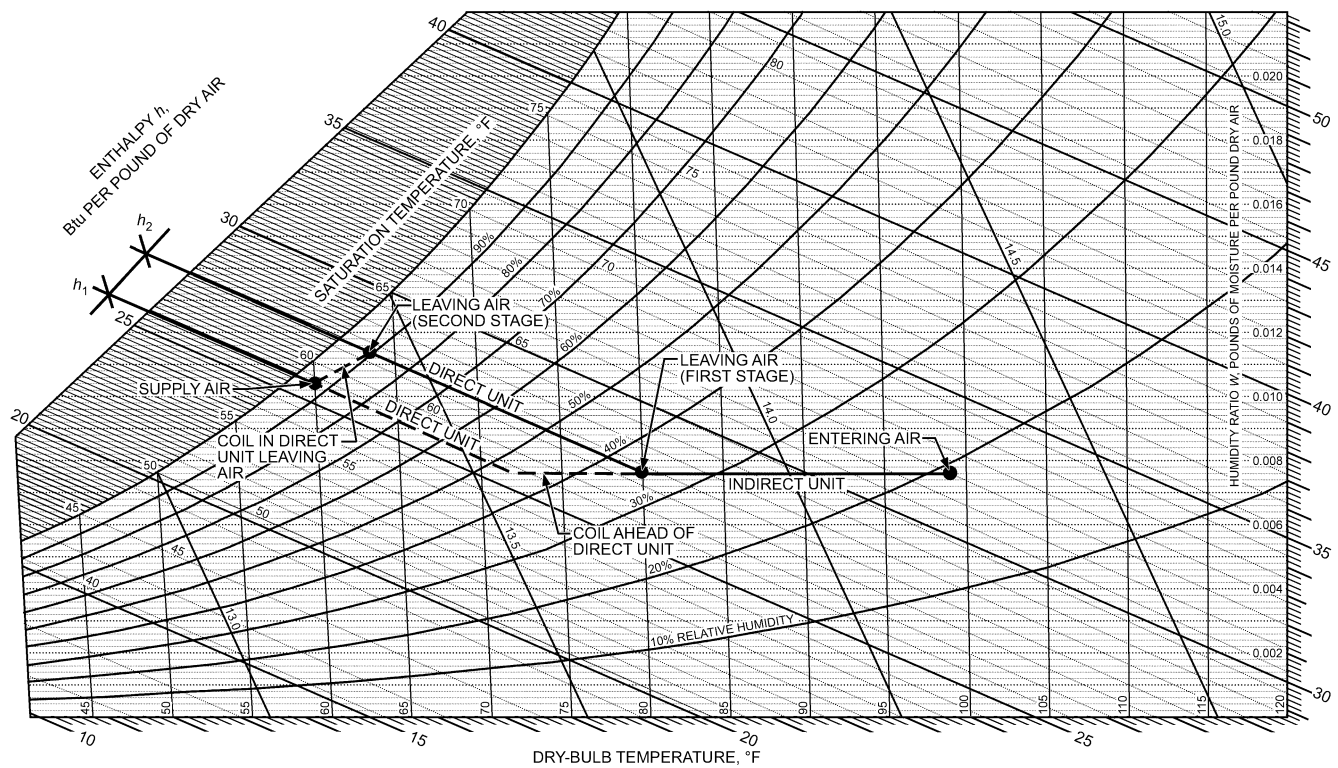
Fig. 20   Psychrometric Diagram of Three-Stage Evaporative Cooling Example 3

Using this example, refrigeration sizing can be compared to conventional refrigeration without staged evaporative cooling. Assuming mixed air conditions to the coil of 81°F db and 66.5°F wb, and the same 60°F db supply air as shown in Figure 20, the refrigerated capacity is

$$60(31.1 - 25.7)24,000/13.31 = 584,200 \text{ Btu/h} = 48.7 \text{ tons}$$

This represents an increase of 30.4 tons. The staged evaporative effect reduces the required refrigeration by 62.4%.

ENTERING AIR CONSIDERATIONS

The effectiveness of direct and indirect evaporative cooling depends on the entering air condition. Where outside air is used in a direct evaporative cooler, the design is affected by the prevailing outside dry- and wet-bulb temperatures as well as by the application. Where conditioned exhaust air is used as secondary air for indirect evaporative cooling, the design is less affected by local weather conditions, which makes evaporative cooling viable in hot and humid environments.

For example, in arid areas like Reno, Nevada, a simple, direct evaporative cooler with an effectiveness of 80% provides a leaving air temperature of 68°F when dry- and wet-bulb temperatures of the entering air are 96 and 61°F, respectively. In the same location, adding an indirect evaporative precooling stage with an effectiveness of 80% produces a leaving air condition of 53.6°F.

In a location such as Atlanta, Georgia, with design temperatures of 94 and 74°F, the same direct evaporative cooler could supply only 78°F. This could be reduced to 71.1°F by adding an 80% effective indirect evaporative precooling stage (Supple 1982). If exhaust air from the building served is provided at a stable 75°F db and 62.5°F wb, an indirect evaporative precooler could deliver air at 68.8°F, substantially reducing outside air cooling loads. Under these conditions, indirect evaporative precoolers can provide limited dehumidification capabilities.

Long-term benefits to owners of direct evaporative cooling systems include a 20 to 40% reduction of utility costs compared to mechanical refrigeration (Watt 1988). When used to control humidity, the reduction in cooling and humidification energy use ranges from 35 to 90% (Lentz 1991). Although direct evaporative cooling does not reduce peak cooling loads in other than arid areas, it can reduce both total cooling energy and humidification energy requirements in a wide range of environments, including hot and humid ones.

Indirect evaporative cooling lowers the temperature (both dry- and wet-bulb) of the air entering a direct evaporative cooling stage and, consequently, lowers the supply air temperature. When used with mechanical cooling on 100% outside air systems, with the secondary air taken from the conditioned space, the precooling effect may reduce peak cooling loads between 50 and 70%. Total cooling requirements may be reduced between 40 and 85% annually depending on location, system configuration, and load characteristics. Indirect evaporative coolers may also function as heat recovery systems, which expands the range of conditions over which the process is used. Indirect evaporative cooling, when used with building exhaust air, is especially effective in hot and humid climates.

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CHAPTER 52

FIRE AND SMOKE MANAGEMENT

IN building fires, smoke often flows to locations remote from the fire, threatening life and damaging property. Stairwells and elevators frequently fill with smoke, thereby blocking or inhibiting evacuation. Smoke causes the most deaths in fires. **Smoke** includes airborne solid and liquid particles and gases produced when a material undergoes pyrolysis or combustion, together with air that is entrained or otherwise mixed into the mass.

The idea of using pressurization to prevent smoke infiltration of stairwells began to attract attention in the late 1960s. This concept was followed by the idea of the pressure sandwich (i.e., venting or exhausting the fire floor and pressurizing the surrounding floors). Frequently, a building's ventilation system is used for this purpose. **Smoke control** systems use fans to pressurize appropriate areas to limit smoke movement in fire situations. **Smoke management** systems include pressurization and all other methods that can be used singly or in combination to modify smoke movement.

This chapter discusses fire protection and smoke control systems in buildings as they relate to HVAC. For a more complete discussion, refer to *Principles of Smoke Management* (Klote and Milke 2002). National Fire Protection Association (NFPA) *Standard* 204 provides information about venting large industrial and storage buildings. For further information, refer to NFPA *Standards* 92A and 92B.

The objective of fire safety is to provide some degree of protection for a building's occupants, the building and property inside it, and neighboring buildings. Various forms of analysis have been used to quantify protection. Specific life safety objectives differ with occupancy; for example, nursing home requirements are different from those for office buildings.

Two basic approaches to fire protection are (1) to prevent fire ignition and (2) to manage fire effects. Figure 1 shows a decision tree for fire protection. Building occupants and managers have the primary role in preventing fire ignition. The building design team may incorporate features into the building to assist the occupants and managers in this effort. Because it is impossible to prevent fire ignition completely, managing fire effect has become significant in fire protection design. Examples include compartmentation, suppression, control of construction materials, exit systems, and smoke management. The *Fire Protection Handbook* (NFPA 2003) and *Smoke Movement and Control in High-Rise Buildings* (Tamura 1994) contain detailed fire safety information.

Historically, fire safety professionals have considered the HVAC system a potentially dangerous penetration of natural building membranes (walls, floors, etc.) that can readily transport smoke and fire. For this reason, HVAC has traditionally been shut down when fire is discovered; this prevents fans from forcing smoke flow, but does not prevent ducted smoke movement caused by buoyancy, stack effect, or wind. To solve the problem of smoke movement, methods of smoke control have been developed; however, smoke control should be viewed as only one part of the overall building fire protection system.

FIRE MANAGEMENT

Although most of this chapter discusses smoke management, fire management at HVAC penetrations is an additional concern for the HVAC engineer. The most efficient way to limit fire damage is through compartmentation. Fire-rated assemblies, such as the floor or walls, keep the fire in a given area for a specific period. However, fire can easily pass through openings for plumbing, HVAC ductwork, communication cables, or other services. Therefore, fire stop systems are installed to maintain the rating of the fire-rated assembly. The rating of a fire stop system depends on the number, size, and type of penetrations, and the construction assembly in which it is installed.

Performance of the entire fire stop system, which includes the construction assembly with its penetrations, is tested under fire conditions by recognized independent testing laboratories. ASTM *Standard* E814 and UL *Standard* 1479 describe ways to determine performance of **through-penetration fire stopping (TPFS)**.

TPFS is required by building codes under certain circumstances for specific construction types and occupancies. In the United States, model building codes require that most penetrations meet the ASTM E814 test standard. TPFS classifications are published by testing laboratories. Each classification is proprietary, and each applies to use with a specific set of conditions, so numerous types are usually required on any given project.

The construction manager and general contractor, not the architects and engineers, make work assignments. Sometimes they assign fire stopping to the discipline making the penetration; other times, they assign it to a specialty fire-stopping subcontractor. The

```
            ┌──────────────┐
            │ FIRE SAFETY  │
            │  OBJECTIVES  │
            └──────┬───────┘
                ( OR )
          ┌─────────┴──────────┐
   ┌──────────────┐     ┌──────────────┐
   │ PREVENT FIRE │     │ MANAGE FIRE  │
   │   IGNITION   │     │    EFFECT    │
   └──────┬───────┘     └──────┬───────┘
       ( OR )                ( OR )
    ┌─────┼─────┐          ┌────┴────┐
```

| CONTROL HEAT-ENERGY SOURCES | CONTROL SOURCE/FUEL INTERACTIONS | CONTROL FUEL | MANAGE THREAT* | MANAGE EXPOSURE* |
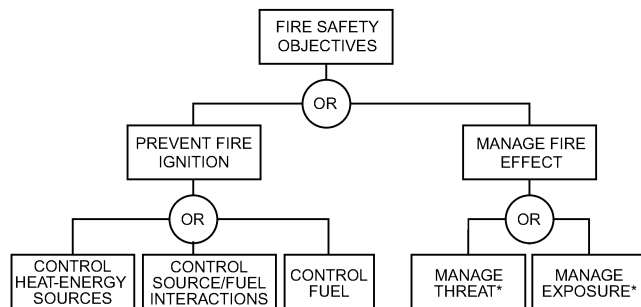
Note: Smoke management is one of many fire protection tools that can be used to help manage the threat and exposure of fire.

Fig. 1 Simplified Fire Protection Decision Tree

The preparation of this chapter is assigned to TC 5.6, Control of Fire and Smoke.

Construction Specifications Institute (CSI) assigns fire-stopping specifications to Division 7, which

- Encourages continuity of fire-stopping products on the project by consolidating their requirements (e.g., TPFS, expansion joint fire stopping, floor-to-wall joint fire stopping, etc.)
- Maintains flexibility of work assignments for the general contractor and construction manager
- Encourages prebid discussions between the contractor and subcontractors regarding appropriate work assignments

SMOKE MOVEMENT

A smoke control system must be designed so that it is not overpowered by the driving forces that cause smoke movement, which include stack effect, buoyancy, expansion, wind, and the HVAC system. During a fire, smoke is generally moved by a combination of these forces.

Stack Effect

When it is cold outside, air tends to move upward within building shafts (e.g., stairwells, elevator shafts, dumbwaiter shafts, mechanical shafts, mail chutes). This **normal stack effect** occurs because air in the building is warmer and less dense than outside air. Normal stack effect is large when outside temperatures are low, especially in tall buildings. However, normal stack effect can exist even in a one-story building.

When outside air is warmer than building air, there is a natural tendency for downward airflow, or **reverse stack effect**, in shafts. At standard atmospheric pressure, the pressure difference caused by either normal or reverse stack effect is expressed as

$$\Delta p = 7.64 \left(\frac{1}{T_o} - \frac{1}{T_i} \right) h \quad (1)$$

where

Δp = pressure difference, in. of water
T_o = absolute temperature of outside air, °R
T_i = absolute temperature of air inside shaft, °R
h = distance above neutral plane, ft

For a building 200 ft tall with a neutral plane at midheight, an outside temperature of 0°F (460°R), and an inside temperature of 70°F (530°R), the maximum pressure difference from stack effect is 0.22 in. of water. This means that, at the top of the building, pressure inside a shaft is 0.22 in. of water greater than the outside pressure. At the base of the building, pressure inside a shaft is 0.22 in. of water
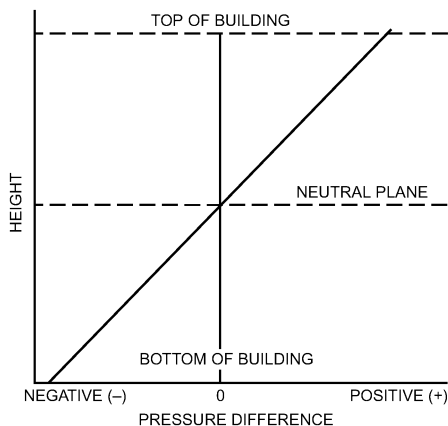
lower than the outside pressure. Figure 2 diagrams the pressure difference between a building shaft and the outside. A positive pressure difference indicates that shaft pressure is higher than the outside pressure, and a negative pressure difference indicates the opposite. Figure 3 illustrates air movement in buildings caused by both normal and reverse stack effect.

Figure 4 can be used to determine the pressure difference caused by stack effect. For normal stack effect, $\Delta p/h$ is positive, and the pressure difference is positive above the neutral plane and negative below it. For reverse stack effect, $\Delta p/h$ is negative, and the pressure difference is negative above the neutral plane and positive below it.

In unusually tight buildings with exterior stairwells, Klote (1980) observed reverse stack effect even with low outside air temperatures. In this situation, the exterior stairwell temperature is considerably lower than the building temperature. The stairwell represents the cold column of air, and other shafts within the building represent the warm columns of air.

If leakage paths are uniform with height, the neutral plane is near the midheight of the building. However, when the leakage paths are not uniform, the location of the neutral plane can vary considerably, as in the case of vented shafts. McGuire and Tamura (1975) provide methods for calculating the location of the neutral plane for some vented conditions.

Smoke movement from a building fire can be dominated by stack effect. In a building with normal stack effect, the existing air currents (as shown in Figure 3) can move smoke considerable distances from the fire origin. If the fire is below the neutral plane, smoke moves
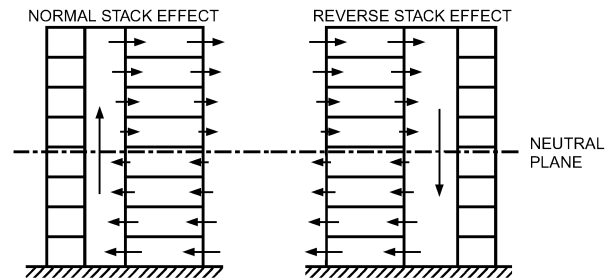
Note: Arrows indicate direction of air movement.

Fig. 3   Air Movement Caused by Normal and Reverse Stack Effect

Fig. 4   Pressure Difference Caused by Stack Effect
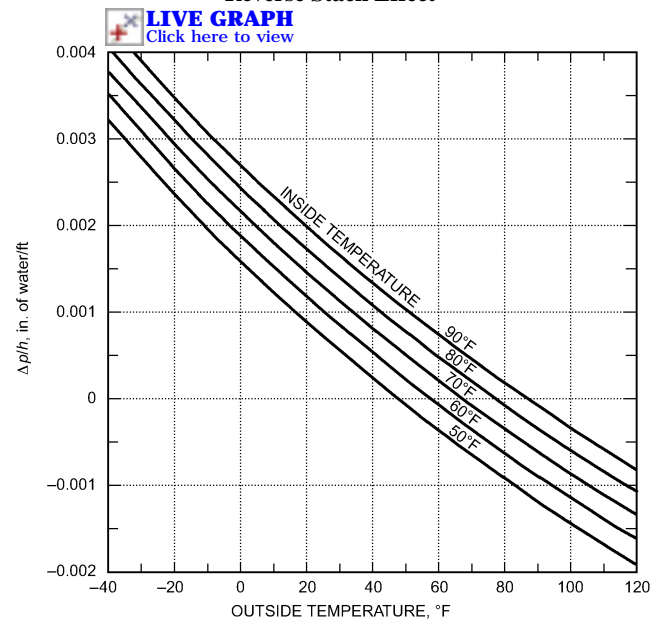
Fig. 2   Pressure Difference Between a Building Shaft and the Outside Caused by Normal Stack Effect

with building air into and up the shafts. This upward smoke flow is enhanced by buoyancy forces due to the temperature of the smoke. Once above the neutral plane, smoke flows from the shafts into the upper floors of the building. If leakage between floors is negligible, floors below the neutral plane (except the fire floor) remain relatively smoke-free until more smoke is produced than can be handled by stack effect flows.

Smoke from a fire located above the neutral plane is carried by building airflow to the outside through exterior openings in the building. If leakage between floors is negligible, all floors other than the fire floor remain relatively smoke-free until more smoke is produced than can be handled by stack effect flows. When leakage between floors is considerable, smoke flows to the floor above the fire floor.

Air currents caused by reverse stack effect (see Figure 3) tend to move relatively cool smoke down. In the case of hot smoke, buoyancy forces can cause smoke to flow upward, even during reverse stack effect conditions.

Buoyancy

High-temperature smoke has buoyancy because of its reduced density. At sea level, the pressure difference between a fire compartment and its surroundings can be expressed as follows:

$$\Delta p = 7.64\left(\frac{1}{T_s} - \frac{1}{T_f}\right)h \tag{2}$$

where

- Δp = pressure difference, in. of water
- T_s = absolute temperature of surroundings, °R
- T_f = average absolute temperature of fire compartment, °R
- h = distance above neutral plane, ft

The pressure difference caused by buoyancy can be obtained from Figure 5 for surroundings at 68°F (328°R). The neutral plane is the plane of equal hydrostatic pressure between the fire compartment and its surroundings. For a fire with a fire compartment temperature at 1470°F (1930°R), the pressure difference 5 ft above the neutral plane is 0.052 in. of water. Fang (1980) studied pressures caused by room fires during a series of full-scale fire tests. During these tests, the maximum pressure difference reached was 0.064 in. of water across the burn room wall at the ceiling.

FIRE COMPARTMENT TEMPERATURE, °F
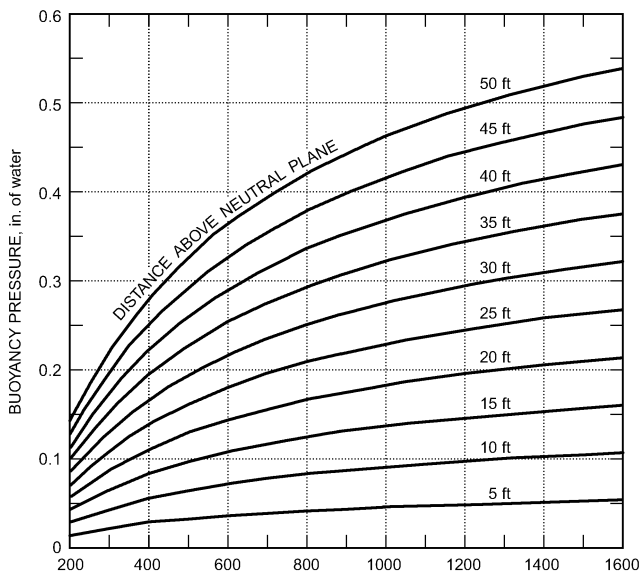
Fig. 5   Pressure Difference Caused by Buoyancy

Much larger pressure differences are possible for tall fire compartments where the distance *h* from the neutral plane can be larger. If the fire compartment temperature is 1290°F (1750°R), the pressure difference 35 ft above the neutral plane is 0.35 in. of water. This is a large fire, and the pressures it produces are beyond present smoke control methods. However, the example illustrates the extent to which Equation (2) can be applied.

In sprinkler-controlled fires, the temperature in the fire room remains at that of the surroundings except for a short time before sprinkler activation. Sprinklers are activated by the **ceiling jet**, a thin (2 to 4 in.) layer of hot gas under the ceiling. The maximum temperature of the ceiling jet depends on the location of the fire, the activation temperature of the sprinkler, and the thermal lag of the sprinkler heat-responsive element. For most residential and commercial applications, the ceiling jet is between 180 and 300°F. In Equation (2), T_f is the average temperature of the fire compartment. For a sprinkler-controlled fire,

$$T_f = \frac{T_s(H - H_j) + T_j H_j}{H} \tag{3}$$

where

- H = floor-to-ceiling height, ft
- H_j = thickness of ceiling jet, ft
- T_j = absolute temperature of ceiling jet, °R

For example, for H = 96 in., H_j = 4 in., T_s = 68 + 460 = 528°R, and T_j = 300 + 460 = 760°R,

$$T_f = [528(96 - 4) + 760 \times 4]/96 = 538°R \text{ or } 78°F$$

In Equation (2), this results in a pressure difference of 0.002 in. of water, which is insignificant for smoke control applications.

Expansion

Energy released by a fire can also move smoke by expansion. In a fire compartment with only one opening to the building, building air will flow in, and hot smoke will flow out. Neglecting the added mass of the fuel, which is small compared to airflow, the ratio of volumetric flows can be expressed as a ratio of absolute temperatures:

$$\frac{Q_{out}}{Q_{in}} = \frac{T_{out}}{T_{in}} \tag{4}$$

where

- Q_{out} = volumetric flow rate of smoke out of fire compartment, cfm
- Q_{in} = volumetric flow rate of air into fire compartment, cfm
- T_{out} = absolute temperature of smoke leaving fire compartment, °R
- T_{in} = absolute temperature of air into fire compartment, °R

For smoke at 1290°F (1750°R) and entering air at 67°F (527°R), the ratio of volumetric flows is 3.32. Note that absolute temperatures are used in the calculation. In such a case, if air enters the compartment at 3000 cfm, then smoke flows out at 9960 cfm, with the gas expanding to more than three times its original volume.

For a fire compartment with open doors or windows, the pressure difference across these openings caused by expansion is negligible. However, for a tightly sealed fire compartment, the pressure differences from expansion may be important.

Wind

Wind can have a pronounced effect on smoke movement within a building. The pressure wind exerts on a surface can be expressed as

$$p_w = 0.00643 C_w \rho_o V^2 \tag{5}$$

where

- p_w = pressure exerted by wind, in. of water
- C_w = pressure coefficient, dimensionless

ρ_o = outside air density, lb_m/ft^3
V = wind velocity, mph

The pressure coefficients C_w are in the range of –0.8 to 0.8, with positive values for windward walls and negative values for leeward walls. The pressure coefficient depends on building geometry and varies locally over the wall surface. In general, wind velocity increases with height from the surface of the earth. Houghton and Carruther (1976), MacDonald (1975), Sachs (1972), and Simiu and Scanlan (1978) give detailed information concerning wind velocity variations and pressure coefficients. Shaw and Tamura (1977) developed specific information about wind data with respect to air infiltration in buildings.

With a pressure coefficient of 0.8 and air density of 0.075 lb_m/ft^3, a 35 mph wind produces a pressure on a structure of 0.47 in. of water. The effect of wind on air movement within tightly constructed buildings with all exterior doors and windows closed is slight. However, wind effects can be important for loosely constructed buildings or for buildings with open doors or windows. Usually, the resulting airflows are complicated, and computer analysis is required.

Frequently, a window breaks in the fire compartment. If the window is on the leeward side of the building, the negative pressure caused by the wind vents the smoke from the fire compartment. This reduces smoke movement throughout the building. However, if the broken window is on the windward side, wind forces the smoke throughout the fire floor and to other floors, which endangers the lives of building occupants and hampers fire fighting. Wind-induced pressure in this situation can be large and can dominate air movement throughout the building.

HVAC Systems

Before methods of smoke control were developed, HVAC systems were shut down when fires were discovered because the systems frequently transported smoke during fires.

In the early stages of a fire, the HVAC system can aid in fire detection. When a fire starts in an unoccupied portion of a building, the system can transport the smoke to a space where people can smell it and be alerted to the fire. However, as the fire progresses, the system transports smoke to every area it serves, thus endangering life in all those spaces. The system also supplies air to the fire space, which aids combustion. Although shutting the system down prevents it from supplying air to the fire, it does not prevent smoke movement through the supply and return air ducts, air shafts, and other building openings because of stack effect, buoyancy, or wind.

SMOKE MANAGEMENT

In this chapter, smoke management includes all methods that can be used singly or in combination to modify smoke movement for the benefit of occupants or firefighters or for reducing property damage. Barriers, smoke vents, and smoke shafts are traditional methods of smoke management. The effectiveness of barriers is limited by the extent to which they are free of leakage paths. Smoke vents and smoke shafts are limited by the fact that smoke must be sufficiently buoyant to overcome any other driving forces that could be present. In the last few decades, fans have been used to overcome the limitations of traditional approaches. Compartmentation, dilution, pressurization, airflow, and buoyancy are used by themselves or in combination to manage smoke conditions in fire situations. These mechanisms are discussed in the following sections.

Compartmentation

Barriers with sufficient fire endurance to remain effective throughout a fire exposure have long been used to protect against fire spread. In this approach, walls, partitions, floors, doors, and other barriers provide some level of smoke protection to spaces remote from the fire. This section discusses passive compartmentation; using compartmentation with pressurization is discussed in the section on Pressurization (Smoke Control). Many codes, such as NFPA *Standard* 101, provide specific criteria for construction of smoke barriers (including doors) and their smoke dampers. The extent to which smoke leaks through such barriers depends on the size and shape of the leakage paths in the barriers and the pressure difference across the paths.

Dilution Remote from Fire

Smoke dilution is sometimes referred to as **smoke purging**, **smoke removal**, **smoke exhaust**, or **smoke extraction**. Dilution can be used to maintain acceptable gas and particulate concentrations in a compartment subject to smoke infiltration from an adjacent space. It can be effective if the rate of smoke leakage is small compared to either the total volume of the safeguarded space or the rate of purging air supplied to and removed from the space. Also, dilution can be beneficial to the fire service for removing smoke after a fire has been extinguished. Sometimes, when doors are opened, smoke flows into areas intended to be protected. Ideally, the doors are only open for short periods during evacuation. Smoke that has entered spaces remote from the fire can be purged by supplying outside air to dilute the smoke.

The following is a simple analysis of smoke dilution for spaces in which there is no fire. Assume that at time zero ($\theta = 0$), a compartment is contaminated with some concentration of smoke and that no more smoke flows into the compartment or is generated within it. Also, assume that the contaminant is uniformly distributed throughout the space. The concentration of contaminant in the space can be expressed as

$$\frac{C}{C_o} = e^{-at} \tag{6}$$

The dilution rate can be determined from the following equation:

$$a = \frac{1}{t}\ln\left(\frac{C_o}{C}\right) \tag{7}$$

where

C_o = initial concentration of contaminant
C = concentration of contaminant at time θ
a = dilution rate, air changes per minute
t = time after smoke stops entering space or smoke production has stopped, min
e = base of natural logarithm (approximately 2.718)

Concentrations C_o and C must be expressed in the same units, but can be any units appropriate for the particular contaminant being considered.

McGuire et al. (1970) evaluated the maximum levels of smoke obscuration from a number of fire tests and a number of proposed criteria for tolerable levels of smoke obscuration. Based on this evaluation, they state that the maximum levels of smoke obscuration are greater by a factor of 100 than those relating to the limit of tolerance. Thus, they indicate that a space can be considered "reasonably safe" with respect to smoke obscuration if the concentration of contaminants in the space is less than about 1% of the concentration in the immediate fire area. This level of dilution increases visibility by about a factor of 100 (e.g., from 0.5 ft to 50 ft) and reduces the concentrations of toxic smoke components. Toxicity is a more complex problem, and no parallel statement has been made regarding dilution needed to obtain a safe atmosphere with respect to toxic gases.

In reality, it is impossible to ensure that the concentration of the contaminant is uniform throughout the compartment. Because of buoyancy, it is likely that higher concentrations are near the ceiling. Therefore, exhausting smoke near the ceiling and supplying air near the floor probably dilutes smoke even more quickly than indicated by Equation (7). Supply and exhaust points should be placed to

prevent supply air from blowing into the exhaust inlet, thereby short-circuiting the dilution.

Example 1. A space is isolated from a fire by smoke barriers and self-closing doors, so that no smoke enters the compartment when the doors are closed. When a door is opened, smoke flows through the open doorway into the space. If the door is closed when the contaminant in the space is 20% of the burn room concentration, what dilution rate is required to reduce the concentration to 1% of that in the burn room in 6 min?

The time $t = 6$ min and $C_o/C = 20$. From Equation (7), the dilution rate is about 0.5 air changes per minute, or 30 air changes per hour.

Caution about Dilution near Fire. Many people have unrealistic expectations about what dilution can accomplish in the fire space. Neither theoretical nor experimental evidence indicates that using a building's HVAC system for smoke dilution will significantly improve tenable conditions in a fire space. The exception is an unusual space where the fuel is such that fire size cannot grow above a specific limit; this occurs in some tunnels and underground transit situations. Because HVAC systems promote a considerable degree of air mixing in the spaces they serve and because very large quantities of smoke can be produced by building fires, it is generally believed that smoke dilution by an HVAC system in the fire space does not improve tenable conditions in that space. Thus, any attempt to improve hazard conditions in the fire space, or in spaces connected to the fire space by large openings, with smoke purging will be ineffective.

Pressurization (Smoke Control)

Systems that pressurize an area using mechanical fans are referred to as smoke control in this chapter and in NFPA *Standard* 92A. A pressure difference across a barrier can control smoke movement, as illustrated in Figure 6. Within the barrier is a door. The high-pressure side of the door can be either a refuge area or an egress route. The low-pressure side is exposed to smoke from a fire. Airflow through gaps around the door and through construction cracks prevents smoke infiltration to the high-pressure side.

For smoke control analysis, the orifice equation can be used to estimate the flow through building flow paths:

$$Q = 776CA\sqrt{2\Delta p/\rho} \tag{8}$$

where

Q = volumetric airflow rate, cfm
C = flow coefficient
A = flow area (leakage area), ft^2
Δp = pressure difference across flow path, in. of water
ρ = density of air entering flow path, lb$_m$/ft^3
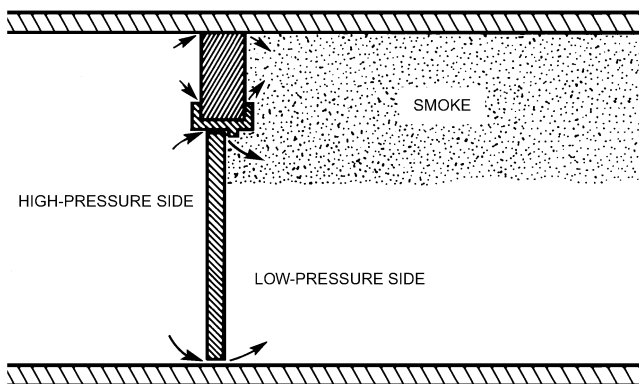
Fig. 6   Smoke Control System Preventing Smoke Infiltration to High-Pressure Side of Barrier

The flow coefficient depends on the geometry of the flow path, as well as on turbulence and friction. In the present context, the flow coefficient is generally 0.6 to 0.7. For $\rho = 0.075$ lb$_m$/ft^3 and $C = 0.65$, Equation (8) can be expressed as

$$Q = 2610A\sqrt{\Delta p} \tag{9}$$

The flow area is frequently the same as the cross-sectional area of the flow path. A closed door with a crack area of 0.11 ft^2 and a pressure difference of 0.01 in. of water has an air leakage rate of approximately 29 cfm. If the pressure difference across the door is increased to 0.30 in. of water, the flow is 157 cfm.

Frequently, in field tests of smoke control systems, pressure differences across partitions or closed doors have fluctuated by as much as 0.02 in. of water. These fluctuations have generally been attributed to wind, although they could have been due to the HVAC system or some other source. To control smoke movement, the pressure difference produced by a smoke control system must be large enough to overcome pressure fluctuations, stack effect, smoke buoyancy, and wind pressure. However, the pressure difference should not be so large that the door is difficult to open.

Airflow

Airflow has been used extensively to manage smoke from fires in subway, railroad, and highway tunnels (see Chapter 13). Large airflow rates are needed to control smoke flow, and these flow rates can supply additional oxygen to the fire. Because of the need for complex controls, airflow is not used as extensively in buildings. The control problem consists of having very small flows when a door is closed and then significantly increased flows when that door is open. Furthermore, it is a major concern that the airflow supplies oxygen to the fire. This section presents the basics of smoke control by airflow and demonstrates why this technique is rarely recommended.

Thomas (1970) determined that in a corridor in which there is a fire, airflow can almost totally prevent smoke from flowing upstream of the fire. Molecular diffusion is believed to transfer trace amounts of smoke, which are not hazardous but which are detectable as the smell of smoke upstream. Based on work by Thomas, the critical air velocity for most applications can be approximated as

$$V_k = 5.68\left(\frac{q_c}{W}\right)^{1/3} \tag{10}$$

where

V_k = critical air velocity to prevent smoke backflow, fpm
q_c = heat release rate into corridor, Btu/h
W = corridor width, ft

This relation can be used when the fire is in the corridor or when smoke enters the corridor through an open doorway, air transfer grille, or other opening. Although critical velocities calculated from Equation (10) are general and approximate, they indicate the kind of air velocities required to prevent smoke backflow from fires of different sizes. For specific applications, other equations may be more appropriate: for tunnel applications, see Chapter 13; for smoke management in atriums and other large spaces, see Klote and Milke (2002) and NFPA *Standard* 92B.

Although Equation (10) can be used to estimate the airflow rate necessary to prevent smoke backflow through an open door, the oxygen supplied is a concern. Huggett (1980) evaluated the oxygen consumed in the combustion of numerous natural and synthetic solids. He found that, for most materials involved in building fires, the energy released is approximately 5630 Btu per pound of oxygen. Air is 23.3% oxygen by mass. Thus, if all the oxygen in a pound of air is consumed, 1300 Btu is liberated. If all the oxygen in 1 cfm of air with a density of 0.075 lb$_m$/ft^3 is consumed by fire, 5850 Btu/h is liberated.

Examples 2 and 3 demonstrate that the air needed to prevent smoke backflow can support an extremely large fire. Most commercial and residential buildings contain enough fuel (paper, cardboard, furniture, etc.) to support very large fires. Even when the amount of fuel is normally very small, short-term fuel loads (during building renovation, material delivery, etc.) can be significant. Therefore, using airflow for smoke control is not recommended, except when the fire is suppressed or in the rare cases when fuel can be restricted with confidence.

Example 2. What airflow at a doorway is needed to stop smoke backflow from a room fully involved in fire, and how large a fire can this airflow support?

A room fully involved in fire can have an energy release rate on the order of 8×10^6 Btu/h. Assume the door is 3 ft wide and 7 ft high. From Equation (10), $V_k = 5.68(8 \times 10^6/3)^{1/3} = 790$ fpm. A flow through the doorway of $790 \times 3 \times 7 = 16{,}600$ cfm is needed to prevent smoke from backflowing into the area.

If all the oxygen in this airflow is consumed in the fire, the heat liberated is 16,600 cfm $\times$ 5850 Btu/h·cfm = 9.7×10^7 Btu/h. This is over 10 times more than the heat generated by the fully involved room fire and indicates why airflow is generally not recommended for smoke control in buildings.

Example 3. What airflow is needed to stop smoke backflow from a wastebasket fire, and how large a fire can this airflow support?

A wastebasket fire can have an energy release rate on the order of 5×10^5 Btu/h. As in Example 2, $V_k = 5.68(5 \times 10^5/3)^{1/3} = 310$ fpm. A flow through the doorway of $310 \times 3 \times 7 = 6500$ cfm is needed to prevent smoke backflow.

If all the oxygen in this airflow is consumed in the fire, the heat liberated is 6500 cfm $\times$ 5850 Btu/h·cfm = 3.8×10^7 Btu/h. This is still many times greater than the fully involved room fire and further indicates why airflow is generally not recommended for smoke control in buildings.

Buoyancy

The buoyancy of hot combustion gases is used in both fan-powered and non-fan-powered venting systems. Fan-powered venting for large spaces is commonly used for atriums and covered shopping malls, and non-fan-powered venting is commonly used for large industrial and storage buildings. There is a concern that sprinkler flow will cool the smoke, reducing buoyancy and thus the system effectiveness. Research is needed in this area. Refer to Klote and Milke (2002) and NFPA *Standards* 92B and 204 for detailed design information about these systems.

SMOKE CONTROL SYSTEM DESIGN

Door-Opening Forces

The door-opening forces resulting from the pressure differences produced by a smoke control system must be considered. Unreasonably high door-opening forces can make it difficult or impossible for occupants to open doors to refuge areas or escape routes.

The force required to open a door is the sum of the forces to overcome the pressure difference across the door and to overcome the door closer. This can be expressed as

$$F = F_{dc} + \frac{5.20\,WA\,\Delta p}{2(W - d)} \tag{11}$$

where

F = total door-opening force, lb_f
F_{dc} = force to overcome door closer, lb_f
W = door width, ft
A = door area, ft^2
Δp = pressure difference across door, in. of water
d = distance from doorknob to edge of knob side of door, ft

This relation assumes that the door-opening force is applied at the knob. Door-opening force F_p caused by pressure difference can
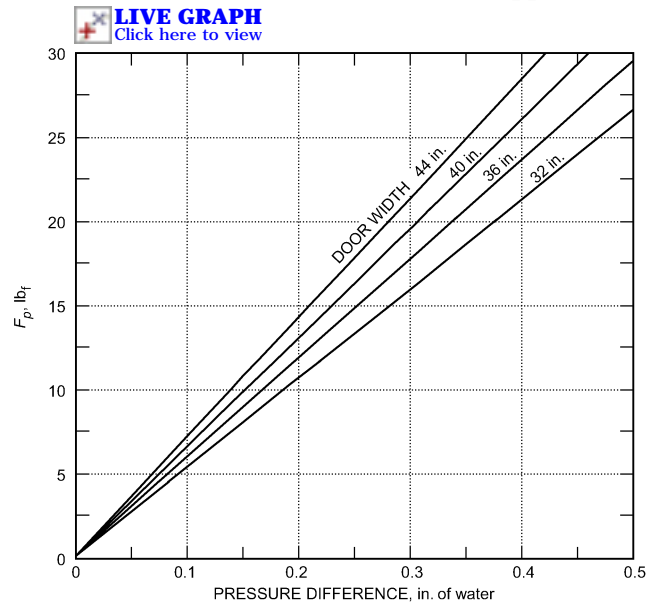
Fig. 7 Door-Opening Force Caused by Pressure Difference

be determined from Figure 7 for a value of $d = 3$ in. The force to overcome the door closer is usually greater than 3 lb_f and, in some cases, can be as great as 20 lb_f. For a door that is 7 ft high and 3 ft wide and subject to a pressure difference of 0.30 in. of water, the total door-opening force is 30 lb_f, if the force to overcome the door closer is 12 lb_f.

Flow Areas

In designing smoke control systems, airflow paths must be identified and evaluated. Some leakage paths are obvious, such as cracks around closed doors, open doors, elevator doors, windows, and air transfer grilles. Construction cracks in building walls are less obvious, but they are equally important.

The flow area of most large openings, such as open windows, can be calculated easily. However, flow areas of cracks are more difficult to evaluate. The area of these leakage paths depends on such features as workmanship, door fit, and weatherstripping. A 3 by 7 ft door with an average crack width of 1/8 in. has a leakage area of 0.21 ft^2. However, if this door is installed with a 3/4 in. undercut, the leakage area is 0.36 ft^2, a significant difference. The leakage area of elevator doors is in the range of 0.55 to 0.70 ft^2 per door.

For open stairwell doorways, Cresci (1973) found complex flow patterns; the resulting flow through open doorways was considerably below that calculated using the doorway's geometric area as the flow area in Equation (8). Based on this research, it is recommended that the design flow area of an open stairwell doorway be *half* the geometric area (door height × width) of the doorway. An alternative for open stairwell doorways is to use the geometric area as the flow area and use a reduced flow coefficient. Because it does not allow the direct use of Equation (8), this approach is not used here.

Typical leakage areas for walls and floors of commercial buildings are tabulated as area ratios in Table 1. These data are based on a relatively small number of tests performed by the National Research Council of Canada (Shaw et al. 1993; Tamura and Shaw 1976a, 1976b, 1978; Tamura and Wilson 1966). Actual leakage areas depend primarily on workmanship rather than on construction materials, and in some cases, the flow areas in particular buildings may vary from the values listed. Data concerning air leakage through building components are also provided in Chapter 27 of the 2005 *ASHRAE Handbook—Fundamentals*.

Because a vent surface is usually covered by a louver and screen, a vent's flow area is less than its area (vent height × width). Calculation

Table 1   Typical Leakage Areas for Walls and Floors of Commercial Buildings

Construction Element	Wall Tightness	Area Ratio
		A/A_w
Exterior building walls[a]	Tight	0.50×10^{-4}
(includes construction cracks and	Average	0.17×10^{-3}
cracks around windows and doors)	Loose	0.35×10^{-3}
	Very Loose	0.12×10^{-2}
Stairwell walls[a]	Tight	0.14×10^{-4}
(includes construction cracks but not	Average	0.11×10^{-3}
cracks around windows or doors)	Loose	0.35×10^{-3}
Elevator shaft walls[a]	Tight	0.18×10^{-3}
(includes construction cracks but	Average	0.84×10^{-3}
not cracks around doors)	Loose	0.18×10^{-2}
		A/A_f
Floors[b]	Tight	0.66×10^{-5}
(includes construction cracks and	Average	0.52×10^{-4}
gaps around penetrations)	Loose	0.17×10^{-3}

A = leakage area; A_w = wall area; A_f = floor area

Leakage areas evaluated at [a]0.3 in. of water; [b]0.1 in. of water.

is further complicated because the louver slats are frequently slanted. Manufacturer's data should be used for specific information.

Effective Flow Areas

The concept of effective flow areas is useful for analyzing smoke control systems. The paths in the system can be in parallel with one another, in series, or a combination of parallel and series. The effective area of a system of flow areas is the area that gives the same flow as the system when it is subjected to the same pressure difference over the total system of flow paths. This is similar to the effective resistance of a system of electrical resistances. The effective flow area A_e for **parallel** leakage areas is the sum of the individual leakage paths:

$$A_e = \sum_{i=1}^{n} A_i \qquad (12)$$

where n is the number of flow areas A_i in parallel.

For example, the effective area A_e for the three parallel leakage areas in Figure 8 is

$$A_e = A_1 + A_2 + A_3 \qquad (13)$$

If A_1 is 1.0 ft^2 and A_2 and A_3 are each 0.5 ft^2, then the effective flow area A_e is 2.0 ft^2.

The general rule for any number of leakage areas in **series** is

$$A_e = \left[\sum_{i=1}^{n} \frac{1}{A_i^2} \right]^{-0.5} \qquad (14)$$

where n is the number of leakage areas A_i in series.

Three leakage areas in series from a pressurized space are illustrated in Figure 9. The effective flow area of these paths is

$$A_e = \left(\frac{1}{A_1^2} + \frac{1}{A_2^2} + \frac{1}{A_3^2} \right)^{-0.5} \qquad (15)$$

In smoke control analysis, there are frequently only two paths in series, and the effective leakage area is

$$A_e = \frac{A_1 A_2}{\sqrt{A_1^2 + A_2^2}} \qquad (16)$$
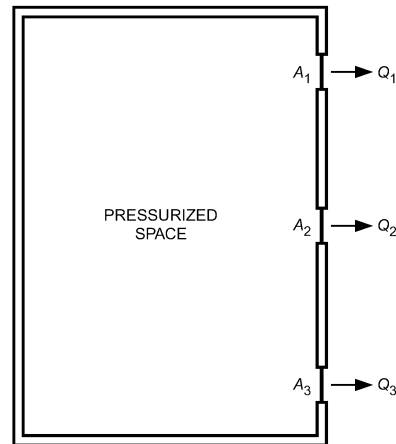
Fig. 8   Leakage Paths in Parallel
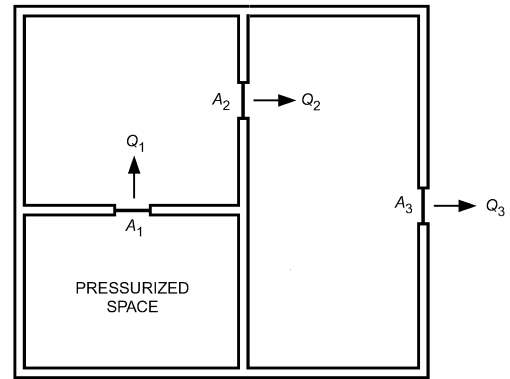
Fig. 9   Leakage Paths in Series

Example 4. Calculate the effective leakage area of two equal flow paths in series. Let $A = A_1 = A_2 = 0.20$ ft^2. From Equation (16),

$$A_e = \frac{A^2}{\sqrt{2A^2}} = 0.14 \text{ ft}^2$$

Example 5. Calculate the effective flow area of two flow paths in series, where $A_1 = 0.20$ ft^2 and $A_2 = 2.0$ ft^2. From Equation (16),

$$A_e = \frac{A_1 A_2}{\sqrt{A_1^2 + A_2^2}} = 0.199 \text{ ft}^2$$

Example 5 illustrates that when two paths are in series, and one is much larger than the other, the effective flow area is approximately equal to the smaller area.

Developing an effective area for a system of both parallel and series paths requires combining groups of parallel paths and series paths systematically. The system illustrated in Figure 10 is analyzed as an example. The figure shows that A_2 and A_3 are in parallel; therefore, their effective area is

$$(A_{23})_e = A_2 + A_3$$

Areas A_4, A_5, and A_6 are also in parallel, so their effective area is

$$(A_{456})_e = A_4 + A_5 + A_6$$

These two effective areas are in series with A_1. Therefore, the effective flow area of the system is given by

$$A_e = \left[\frac{1}{A_1^2} + \frac{1}{(A_{23})_e^2} + \frac{1}{(A_{456})_e^2} \right]^{-0.5}$$
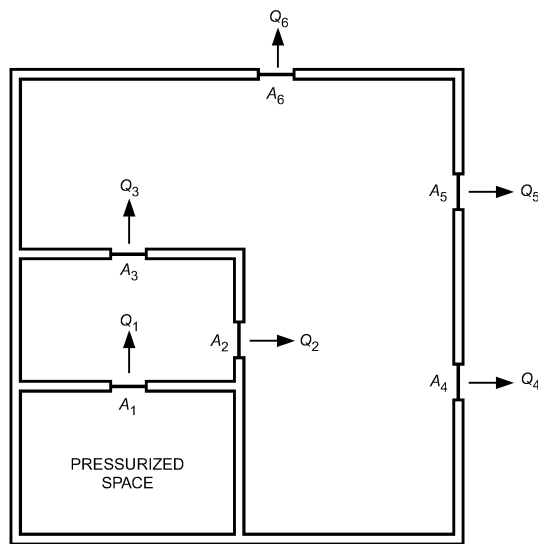
Fig. 10   Combination of Leakage Paths in Parallel and Series

Note: If fans are off, all dampers should be closed.

Fig. 11   Smoke Control System Damper Recommendation

Example 6. Calculate the effective area of the system in Figure 10, if the leakage areas are $A_1 = A_2 = A_3 = 0.2$ ft^2 and $A_4 = A_5 = A_6 = 0.1$ ft^2.

$$(A_{23})_e = 0.4 \text{ ft}^2$$
$$(A_{456})_e = 0.3 \text{ ft}^2$$
$$A_e = 0.15 \text{ ft}^2$$

Design Weather Data

Little weather information has been developed specifically for smoke control system design. Design temperatures for heating and cooling found in Chapter 28 of the 2005 *ASHRAE Handbook—Fundamentals* may be used. Extreme temperatures can be considerably lower than the winter design temperatures. For example, the 99% design temperature for Tallahassee, Florida, is 28°F, but the lowest temperature observed there was −2°F (NOAA 1979).

Temperatures are generally below the design values for short periods, and because of the thermal lag of building materials, these short intervals of low temperature usually do not cause problems with heating. However, there is no time lag for a smoke control system; it is therefore subjected to all the extreme forces of stack effect that exist the moment it operates. If the outside temperature is below the system's winter design temperature, stack effect problems may result. A similar situation can occur with summer design temperatures and reverse stack effect.

Extreme wind data for smoke management design are listed in Chapter 28 of the 2005 *ASHRAE Handbook—Fundamentals*.

Design Pressure Differences

Both the maximum and minimum allowable pressure differences across the boundaries of smoke control should be considered. The maximum allowable pressure difference should not cause excessive door-opening forces.

The minimum allowable pressure difference across a boundary of a smoke control system might be the difference such that no smoke leakage occurs during building evacuation. In this case, the smoke control system must produce sufficient pressure differences to overcome forces of wind, stack effect, or buoyancy of hot smoke. Pressure differences caused by wind and stack effect can be large in the event of a broken window in the fire compartment. Evaluation of these pressure differences depends on evacuation time, rate of fire growth, building configuration, and the presence of a fire suppression system. NFPA *Standard* 92A suggests values of minimum and maximum design pressure difference.
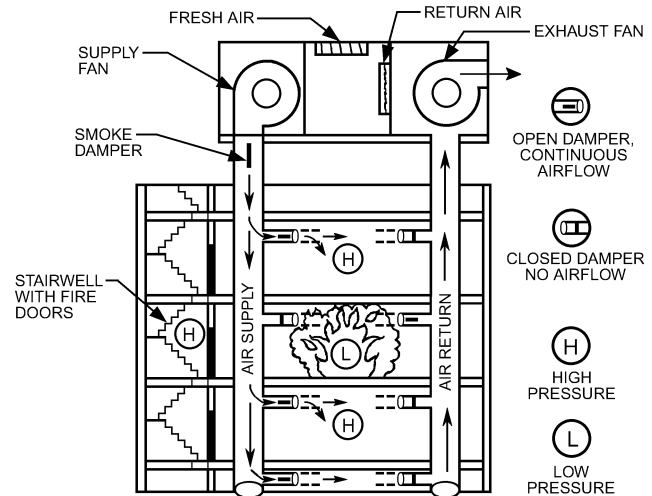
Open Doors

Another design concern is the number of doors that could be opened simultaneously when the smoke control system is operating. A design that allows all doors to be open simultaneously may ensure that the system always works, but often adds to system cost.

The number of doors that may be open simultaneously depends largely on building occupancy. For example, in a densely populated building, it is likely that all doors will be open during evacuation. However, if a staged evacuation plan or refuge area concept is incorporated in the building fire emergency plan, or if the building is sparsely occupied, only a few of the doors may be open during a fire.

FIRE AND SMOKE DAMPERS

Openings for ducts in walls and floors with fire resistance ratings should be protected by fire dampers and ceiling dampers, as required by local codes. Air transfer openings should also be protected. These dampers should be classified and labeled in accordance with Underwriters Laboratories (UL) *Standard* 555. Figure 11 shows recommended damper positions for smoke control.

A smoke damper can be used for either traditional smoke management (smoke containment) or smoke control. In **smoke management**, a smoke damper inhibits passage of smoke under the forces of buoyancy, stack effect, and wind. However, smoke dampers are only one of many elements (partitions, floors, doors) intended to inhibit smoke flow. In smoke management applications, the leakage characteristics of smoke dampers should be selected to be appropriate with the leakage of the other system elements.

In a **smoke control system**, a smoke damper inhibits the passage of air that may or may not contain smoke. A damper does not need low leakage characteristics when outside (fresh) air is on the high-pressure side of the damper, as is the case for dampers that shut off supply air from a smoke zone or that shut off exhaust air from a nonsmoke zone. In these cases, moderate leakage of smoke-free air through the damper does not adversely affect control of smoke movement. It is best to design smoke control systems so that only smoke-free air is on the high-pressure side of a closed smoke damper.

Smoke dampers should be classified and listed in accordance with UL *Standard* 555S for temperature, leakage, and operating velocity. The velocity rating of a smoke damper is the velocity at which the actuator will open and close the damper.

At locations requiring both smoke and fire dampers, combination dampers meeting the requirements of both UL *Standards* 555

and 555S can be used. The combination fire/smoke dampers must close when they reach their UL *Standard* 555S temperature rating to maintain the integrity of the firewall.

Fire, ceiling, and smoke dampers should be installed in accordance with the manufacturers' instructions. NFPA *Standard* 90A gives general guidelines on locations requiring these dampers.

The supply and return/smoke dampers should be a minimum of Class II leakage at 250°F. The return air damper should be a minimum of Class I leakage at 250°F to prevent recirculation of smoke exhaust. The operating velocity of the dampers should be evaluated when the dampers are in smoke control mode. To minimize velocity build-up, only zones adjacent to the fire need to be pressurized.

The exhaust ductwork and fan must be designed to handle the temperature of the exhaust smoke. This temperature can be lowered by making the smoke control zones large or by pressurizing only the zones adjacent to the fire zone and leaving all other zones operating normally.

Fans Used to Exhaust Smoke

Understanding building code requirements for high-temperature fans in smoke control systems is important for both designers, who must select fans that can operate satisfactorily at elevated temperatures, and manufacturers, who can then design suitable off-the-shelf fans rather than customizing fans for each application. Only fans designed for use under elevated temperatures should be used in smoke management applications; other types may fail, or their performance may change because of component deformation or altered clearances among components. Also, some smoke exhaust applications (e.g., transit tunnels) require that smoke-handling fans reverse direction repeatedly on demand. Until recently, standards did not address reversibility or airflow performances of high-temperature fans at ambient and elevated temperatures. To allow manufacturers to provide suitable off-the-shelf products, a standard method of test (MOT) and ratings scale have been developed.

ANSI/ASHRAE *Standard* 149 provides testing laboratories with standard testing methods for fan characteristics specific to smoke exhaust functions, including (1) aerodynamic performance, (2) operation at specified elevated temperature, (3) reversal, and (4) damper performance (for dampers included with the fan).

AMCA *Publication* 212 establishes ratings to allow consistent comparison among catalog test data. Model code requirements for elevated temperature and duration of operation are charted on a graph, which is divided into several fan performance groups. Manufacturers can request that laboratories test fans according to ANSI/ASHRAE *Standard* 149; those data can then be incorporated into catalogs for off-the-shelf products according to AMCA *Publication* 212 ratings, allowing designers to select the most appropriate models and performances for their specific applications. This allows designers and code officials to compare different manufacturers' products more easily, and enhances confidence that products will perform as intended; it also allows manufacturers to provide more cost-efficient off-the-shelf products rather than custom-designing fans for each application.

PRESSURIZED STAIRWELLS

Many pressurized stairwells have been designed and built to provide a smoke-free escape route in the event of a building fire. They also provide a smoke-free staging area for firefighters. On the fire floor, a pressurized stairwell must maintain a positive pressure difference across a closed stairwell door to prevent smoke infiltration.

During building fires, some stairwell doors are opened intermittently during evacuation and fire fighting, and some doors may even be blocked open. Ideally, when the stairwell door is opened on the fire floor, airflow through the door should be sufficient to prevent smoke backflow. Designing a system to achieve this goal is difficult because of the many combinations of open stairwell doors and weather conditions affecting airflow.

Stairwell pressurization systems may be single- or multiple-injection systems. A **single-injection system** supplies pressurized air to the stairwell at one location, usually at the top. Associated with this system is the potential for smoke to enter the stairwell through the pressurization fan intake. Therefore, automatic shutdown during such an event should be considered.

For tall stairwells, single-injection systems can fail when a few doors are open near the air supply injection point, especially in bottom-injection systems when a ground-level stairwell door is open.

For tall stairwells, supply air can be supplied at a number of locations over the height of the stairwell. Figures 12 and 13 show two examples of **multiple-injection systems** that can be used to overcome the limitations of single-injection systems. In these figures, the supply duct is shown in a separate shaft. However, systems have been built that eliminated the expense of a separate duct shaft by locating the supply duct in the stairwell itself. In such a case, care must be taken that the duct does not obstruct orderly building evacuation.

Stairwell Compartmentation

Compartmentation of the stairwell into a number of sections is one alternative to multiple injection (Figure 14). When the doors between compartments are open, the effect of compartmentation is
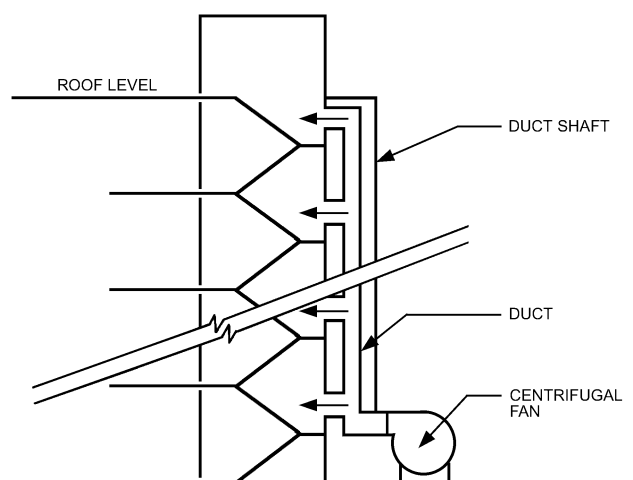
Fig. 12 Stairwell Pressurization by Multiple Injection with Fan Located at Ground Level
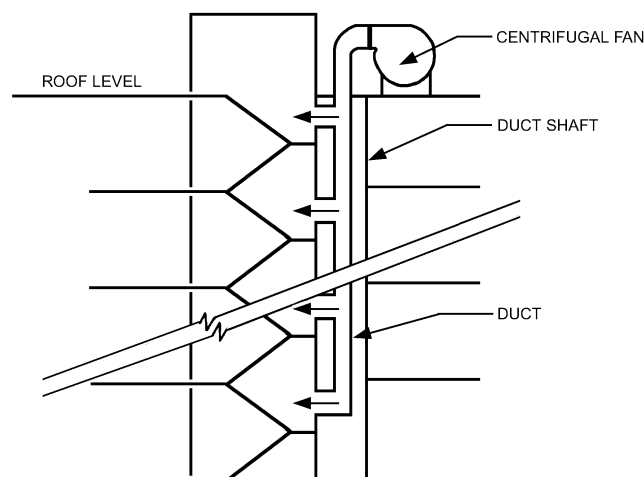
Fig. 13 Stairwell Pressurization by Multiple Injection with Roof-Mounted Fan

ROOF LEVEL

STAIRWELL IS
DIVIDED INTO
COMPARTMENTS

GROUND LEVEL
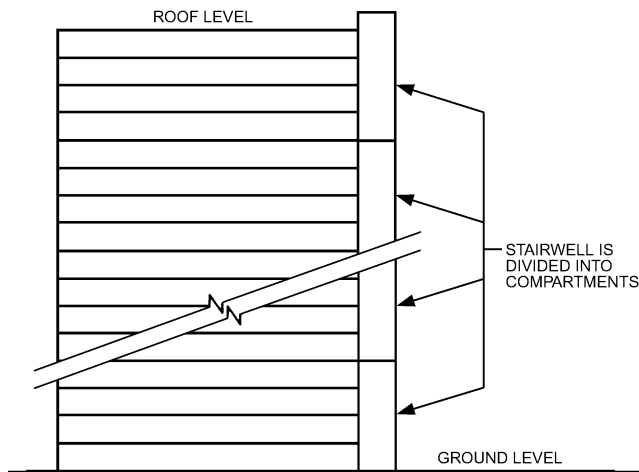
Note: Each four-floor compartment has a least one supply air injection point.

Fig. 14   Compartmentation of Pressurized Stairwell

lost. For this reason, compartmentation is inappropriate for densely populated buildings where total building evacuation by the stairwell is planned in the event of fire. However, when a staged evacuation plan is used and the system is designed to operate successfully with the maximum number of doors between compartments open, compartmentation can effectively pressurize tall stairwells.

Stairwell Analysis

This section presents an analysis for a pressurized stairwell in a building without vertical leakage. This method closely approximates the performance of pressurized stairwells in buildings without elevators. It is also useful for buildings with vertical leakage because it yields conservative results. For evaluating vertical leakage through the building or with open stairwell doors, computer analysis is recommended. The analysis is for buildings where the leakage areas are the same for each floor of the building and where the only significant driving forces are the stairwell pressurization system and the indoor-outdoor temperature difference.

The pressure difference Δp_{sb} between the stairwell and the building can be expressed as

$$\Delta p_{sb} = \Delta p_{sbb} + \frac{By}{1 + (A_{sb}/A_{bo})^2} \qquad (17)$$

where

Δp_{sbb} = pressure difference between stairwell and building at stairwell bottom, in. of water
B = 7.64$(1/T_o - 1/T_s)$ at sea level standard pressure
y = distance above stairwell bottom, ft
A_{sb} = flow area between stairwell and building (per floor), ft^2
A_{bo} = flow area between building and outside (per floor), ft^2
T_o = temperature of outside air, °R
T_s = temperature of stairwell air, °R

For a stairwell with no leakage directly to the outside, the flow rate of pressurization air is

$$Q = 1740 N A_{sb} \left(\frac{\Delta p_{sbt}^{3/2} - \Delta p_{sbb}^{3/2}}{\Delta p_{sbt} - \Delta p_{sbb}} \right) \qquad (18)$$

where

Q = volumetric flow rate, cfm
N = number of floors
Δp_{sbt} = pressure difference from stairwell to building at stairwell top, in. of water

Example 7. Each story of a 15-story stairwell is 10.8 ft high. The stairwell has a single-leaf door at each floor leading to the occupant space and one ground-level door to the outside. The exterior of the building has a wall area of 6030 ft^2 per floor. The exterior building walls and stairwell walls are of average leakiness. The stairwell wall area is 560 ft^2 per floor. The area of the gap around each stairwell door to the building is 0.26 ft^2. The exterior door is well gasketed, and its leakage can be neglected when it is closed.

Outside design temperature T_o = 474°R; stairwell temperature T_s = 530°R; maximum design pressure differences when all stairwell doors are closed is 0.35 in. of water; the minimum allowable pressure difference is 0.052 in. of water.

Using the leakage ratio for an exterior building wall of average tightness from Table 1, A_{bo} = 6030(0.21×10^{-3}) = 1.27 ft^2. Using the leakage ratio for a stairwell wall of average tightness from Table 1, the leakage area of the stairwell wall is 560(0.11×10^{-3}) = 0.06 ft^2. The value of A_{sb} equals the leakage area of the stairwell wall plus the gaps around the closed doors: A_{sb} = 0.06 + 0.26 = 0.32 ft^2. The temperature factor B is calculated at 0.00170 in. of water/ft. The pressure difference at the stairwell bottom is selected as Δp_{sbb} = 0.080 in. of water to provide an extra degree of protection above the minimum allowable value of 0.052 in. of water. The pressure difference Δp_{sbt} is calculated from Equation (17) at 0.339 in. of water, using y = 15(10.8) = 162 ft. Thus, Δp_{sbt} does not exceed the maximum allowable pressure. The flow rate of pressurization air is calculated from Equation (18) at 5640 cfm.

The flow rate depends strongly on the leakage area around the closed doors and on the leakage area in the stairwell walls. In practice, these areas are difficult to evaluate and even more difficult to control. If flow area A_{sb} in Example 7 were 0.54 ft^2 rather than 0.32 ft^2, Equation (18) would give a flow rate of pressurization air of 9500 cfm. A fan with a sheave allows adjustment of supply air to offset for variations in actual leakage from the values used in design calculations.

Stairwell Pressurization and Open Doors

The simple pressurization system discussed in the previous section has two limitations regarding open doors. First, when a stairwell door to the outside and building doors are open, the simple system cannot provide enough airflow through building doorways to prevent smoke backflow. Second, when stairwell doors are open, pressure difference across the closed doors can drop to low levels. Two systems used to overcome these problems are overpressure relief (Tamura 1990) and supply fan bypass.

Overpressure Relief. The total airflow rate is selected to provide the minimum air velocity when a specific number of doors are open. When all the doors are closed, part of this air is relieved through a vent to prevent excessive pressure build-up, which could cause excessive door-opening forces. This excess air should be vented from the stairwell to the street-level floor. Fire and relief dampers should be the low-leakage type. Stairwell doors should have gasket seals at sides and top, leaving the bottom gap open for relief.

Barometric dampers that close when pressure drops below a specified value can minimize air loss through the vent when doors are open. Figure 15 illustrates a pressurized stairwell with overpressure relief vents to the building at each floor. In systems with vents between stairwell and building, the vents typically have a fire damper in series with the barometric damper. To conserve energy, these fire dampers are normally closed, but they open when the pressurization system is activated. This arrangement also reduces the possibility of the annoying damper chatter that frequently occurs with barometric dampers.

An exhaust duct can provide overpressure relief in a pressurized stairwell. The system is designed so that the normal resistance of a nonpowered exhaust duct maintains pressure differences within the design limits.

Exhaust fans can also relieve excess pressure when all stairwell doors are closed. An exhaust fan should be controlled by a differential pressure sensor, so that it will not operate when the pressure difference between stairwell and building falls below a specified level.
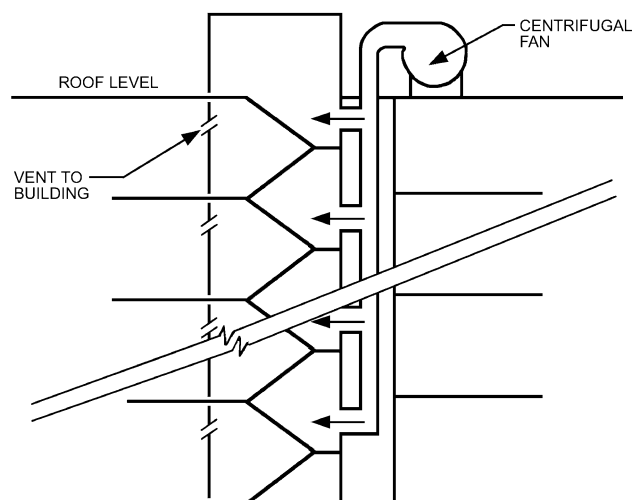
Notes: 1. Vents to building have barometric damper and fire damper in series.
2. Roof-mounted supply fan is shown; however, fan may be located at any level.
3. Manually operated damper may be located at stairwell top for smoke purging by fire department.

Fig. 15   Stairwell Pressurization with Vents to Building at Each Floor

Notes: 1. Fan bypass controlled by one or more static-pressure sensors located between stairwell and building.
2. Roof-mounted supply fan is shown; however, fan may be located at any level.
3. Manually operated damper may be located at stairwell top for smoke purging by fire department.

Fig. 16   Stairwell Pressurization with Bypass Around Supply Fan

This control should prevent the fan from pulling smoke into the stairwell when a number of open doors have reduced stairwell pressurization. The exhaust fan should be specifically sized so that the pressurization system performs within design limits. A wind shield is recommended because an exhaust fan can be adversely affected by the wind.

An alternative method of venting a stairwell is through an automatically opening stairwell door to the outside at ground level. Under normal conditions, this door would be closed and, in most cases, locked for security reasons. Provisions are needed to prevent this lock from conflicting with the automatic operation of the system. Possible adverse wind effects are also a concern with a system that uses an open outside door as a vent. Occasionally, high local wind velocities develop near the exterior stairwell door; such winds are difficult to estimate without expensive modeling. Nearby obstructions can act as windbreaks or wind shields.

Supply Fan Bypass. In this system, the supply fan is sized to provide at least the minimum air velocity when the design number of doors are open. Figure 16 illustrates such a system. The flow rate of air into the stairwell is varied by modulating bypass dampers, which are controlled by one or more static pressure sensors that sense the pressure difference between the stairwell and the building. When all the stairwell doors are closed, the pressure difference increases and the bypass damper opens to increase the bypass air and decrease the flow of supply air to the stairwell. In this manner, excessive stairwell pressures and excessive pressure differences between the stairwell and the building are prevented.

ELEVATORS

Elevator smoke control systems intended for use by firefighters should keep elevator cars, elevator shafts, and elevator machinery rooms smoke-free. Small amounts of smoke in these spaces are acceptable, provided that the smoke is nontoxic and that operation of elevator equipment is not affected. Elevator smoke control systems intended for fire evacuation of people unable to self-rescue or other building occupants should also keep elevator lobbies smoke-free or nearly smoke-free. Obstacles to fire evacuation by elevators include

• Logistics of evacuation
• Reliability of electrical power
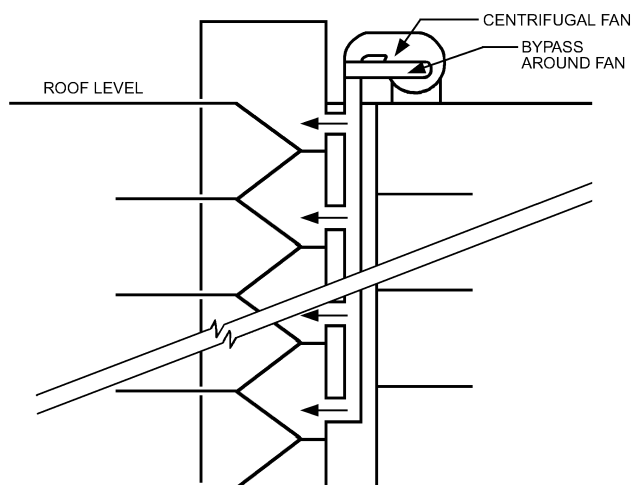
• Jamming of elevator doors
• Fire and smoke protection

All these obstacles, except smoke protection, can be addressed by existing technology (Klote 1984).

Klote and Tamura (1986) studied conceptual elevator smoke control systems for evacuation of people unable to self-rescue. The major problem was maintaining pressurization with open building doors, especially doors on the ground floor. Of the systems evaluated, only one with a supply fan bypass with feedback control maintained adequate pressurization with any combination of open or closed doors. There are probably other systems capable of providing adequate smoke control; the procedure used by Klote and Tamura can be viewed as an example of a method of evaluating the performance of a system to determine whether it suits the particular characteristics of a building under construction.

Transient pressures caused by **piston effect** when an elevator car moves in a shaft have been a concern in elevator smoke control. Piston effect is not a concern for slow-moving cars in multiple-car shafts, but can be considerable for fast cars in single-car shafts.

ZONE SMOKE CONTROL

Klote (1990) conducted a series of tests on full-scale fires that demonstrated that zone smoke control can restrict smoke movement to the zone where a fire starts.

Pressurized stairwells are intended to prevent smoke infiltration into stairwells. However, in a building with only stairwell pressurization, smoke can flow through cracks in floors and partitions and through shafts to damage property and threaten life at locations remote from the fire. Zone smoke control is intended to limit this smoke movement.

A building is divided into a number of smoke control zones, each separated from the others by partitions, floors, and doors that can be closed to inhibit smoke movement. In the event of a fire, pressure differences and airflows produced by mechanical fans limit spread of smoke from the zone in which the fire started. The concentration of smoke in this zone goes unchecked; thus, in zone smoke control systems, occupants should evacuate the smoke zone as soon as possible after fire detection.
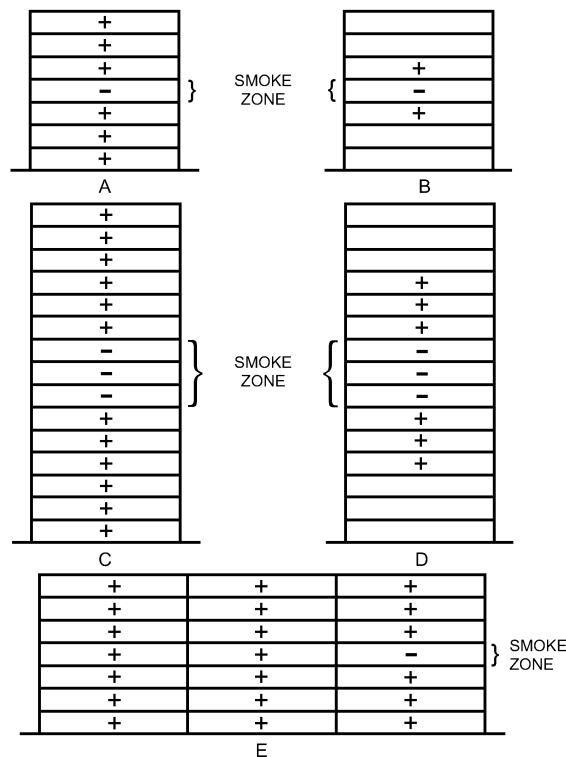
Note:
In the above figures, the smoke zone is indicated by a minus sign, and pressurized spaces are indicated by a plus sign. Each floor can be a smoke control zone as in A and B, or a smoke zone can consist of more than one floor as in C and D. All non-smoke zones adjacent to the smoke zone may be pressurized, as in A and C, or only nonsmoke zones adjacent to the smoke zone may be pressurized, as in B and D. A smoke zone can also be limited to a part of a floor as in E.

Fig. 17 Some Arrangements of Smoke Control Zones

A smoke control zone can consist of one floor, more than one floor, or part of a floor. Sprinkler zones and smoke control zones should be coordinated so that sprinkler water flow activates the zone's smoke control system. Some arrangements of smoke control zones are illustrated in Figure 17. All the nonsmoke zones in the building may be pressurized. The term **pressure sandwich** describes cases where only zones adjacent to the smoke zone are pressurized, as in Figures 17B and 17D.

Zone smoke control is intended to limit smoke movement to the smoke zone by the use of pressurization. Pressure differences in the desired direction across the barriers of a smoke zone can be achieved by supplying outside (fresh) air to nonsmoke zones, by venting the smoke zone, or by a combination of these methods.

Venting smoke from a smoke zone prevents significant overpressure from thermal expansion of gases caused by the fire. This venting can be accomplished by exterior wall vents, smoke shafts, and mechanical venting (exhausting). However, venting only slightly reduces smoke concentration in the smoke zone.

COMPUTER ANALYSIS FOR PRESSURIZATION SYSTEMS

Because of the complex airflow in buildings, network computer programs were developed to model the airflow with pressurization systems. These models represent rooms and shafts by nodes; airflow is from nodes of high pressure to nodes of lower pressure. Some programs calculate steady-state airflow and pressures throughout a building (Sander 1974; Sander and Tamura 1973). Other programs go beyond this to calculate the smoke concentrations that would be produced throughout a building in

the event of a fire (Evers and Waterhouse 1978; Rilling 1978; Wakamatsu 1977; Yoshida et al. 1979).

The ASCOS program was developed specifically for analyzing pressurization smoke control systems (Klote 1982). ASCOS was the most widely used program for smoke control analysis (Said 1988), and has been validated against field data from flow experiments at an eight-story tower in Champs sur Marne, France (Klote and Bodart 1985). ASCOS and the other network models have been used extensively for design and for parametric analysis of the performance of smoke control systems. However, ASCOS was intended as a research tool for application to 10- and 20-story buildings. Not surprisingly, convergence failures have been encountered with applications to much larger buildings.

Wray and Yuill (1993) evaluated several flow algorithms to find the most appropriate one for analysis of smoke control systems. They selected the AIRNET flow routine developed by Walton (1989) as the best algorithm based on computational speed and use of computer memory. None of the algorithms from this study takes advantage of the repetitive nature of building flow networks, so data entry is difficult. However, Walton and Dols (2005) developed CONTAM, a public domain program with an improved version of the AIRNET flow routine and an easier method of input. CONTAM can be downloaded free of charge from http://www.bfrl.nist.gov/IAQ analysis/CONTAM.

These models are appropriate for analyzing systems that use pressurization to control smoke flow. For systems that rely on buoyancy of hot smoke (such as atrium smoke exhaust), **zone fire models** are appropriate. The concepts behind zone fire modeling are discussed by Bukowski (1991), Jones (1983), and Mitler (1985). Some frequently used zone models are ASET (Cooper 1985), CCFM (Cooper and Forney 1987), and CFAST (Peacock et al. 1993). Milke and Mowrer (1994) enhanced the CCFM model for atrium applications.

SMOKE MANAGEMENT IN LARGE SPACES

In recent years, atrium buildings have become commonplace. Other large, open spaces include enclosed shopping malls, arcades, sports arenas, exhibition halls, and airplane hangars. For simplicity, the term **atrium** is used in this chapter in a generic sense to mean any of these large spaces. Traditional fire protection by compartmentation is not applicable to these large-volume spaces.

Most atrium smoke management systems are designed to prevent exposure of occupants to smoke during evacuation; this is the approach described in this section. An alternative goal is to maintain tenable conditions even when occupants have some contact with smoke, as discussed in the section on Tenability Systems.

The following approaches can be used to manage smoke in atriums:

- **Smoke filling.** This approach allows smoke to fill the atrium space while occupants evacuate the atrium. It applies only to spaces where the smoke-filling time is sufficient for both decision making and evacuation. Nelson and Mowrer (2002), Chapter 4 of Klote and Milke (2002), and Proulx (2002) have information on people movement during evacuation. The filling time can be estimated either by zone fire models or by filling equations [e.g., Equation (21)].
- **Unsteady clear height with upper layer exhaust.** This approach exhausts smoke from the top of the atrium at a rate such that occupants have sufficient time for decision making and evacuation. It requires analysis of people movement and fire model analysis of smoke filling.
- **Steady clear height with upper layer exhaust.** This approach exhausts smoke from the top of the atrium to achieve a steady clear height for a steady fire (Figure 18). A calculation method is presented in the section on Steady Clear Height with Upper Layer Exhaust.
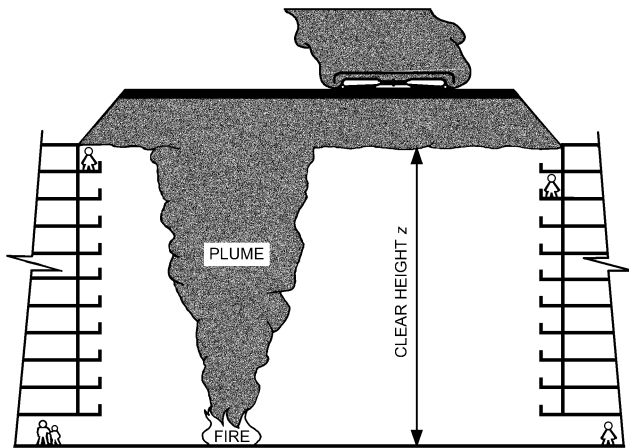
Fig. 18   Smoke Exhaust to Maintain Steady Clear Height

Design Fires

The design fire has a major effect on the atrium smoke management system. Fire size is expressed in terms of rate of heat release. Fire growth is the rate of change of the heat release rate and is sometimes expressed as a growth constant that identifies the time required for the fire to attain a particular rate of heat release. Designs may be based on either steady fires or unsteady fires.

Fires are by nature unsteady, but the steady fire is a very useful idealization. **Steady fires** have a constant heat release rate. In many applications, using a steady design fire leads to straightforward and conservative design.

Morgan (1979) suggests 44 Btu/s·ft^2 as a typical rate of heat release per unit floor area for mercantile occupancies. Fang and Breese (1980) found about the same rate of heat release for residential occupancies. Law (1982) and Morgan and Hansell (1987) suggest a heat release rate per unit floor area for office buildings of 20 Btu/s·ft^2.

In many atriums, fuel loading is severely restricted with the intent of restricting fire size. Such atriums are characterized by interior finishes of metal, brick, stone, or gypsum board and furnished with objects made of similar materials plus plants. Even in such a **fuel-restricted atrium**, many combustible objects are present for short periods. Packing materials, holiday decorations, displays, construction materials, and furniture being moved into another part of the building are a few examples of **transient fuels**.

In this chapter, a heat release rate per floor area of 20 Btu/s·ft^2 is used for a fuel-restricted atrium, and 44 Btu/s·ft^2 is used for atriums containing furniture, wood, or other combustible materials.

Transient fuels must not be overlooked when selecting a design fire. Klote and Milke (2002) suggest incorporating transient fuels in a design fire by considering the fire occurring over 100 ft^2 of floor space. This results in a design fire of 2000 Btu/s for fuel-restricted atriums. In an atrium with combustibles, the design fire would be 4400 Btu/s. However, the area involved in fire may be much greater; flame spread considerations must be taken into account (Klote and Milke 2002; NFPA *Standard* 92B). A large atrium fire of 25,000 Btu/s would involve an area of 568 ft^2 at 44 Btu/s·ft^2. Table 2 lists some steady design fires.

Unsteady fires are often characterized by the following equation:

$$q = 1000\left(\frac{t}{t_g}\right)^2 \qquad (19)$$

where

q = heat release rate of fire, Btu/s
t = time, s
t_g = growth time, s
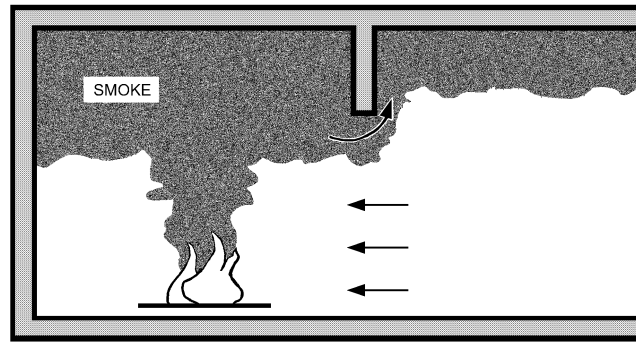
A. SKETCH OF ROOM FIRE
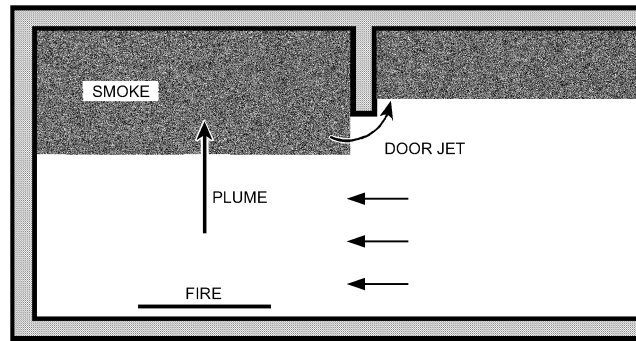
B. ZONE MODEL IDEALIZATION OF ROOM FIRE

Fig. 19   Room Fire and Zone Fire Model Idealization

Table 2   Steady Design Fire Sizes for Atriums

	Btu/s
Minimum fire for fuel-restricted atrium	2,000
Minimum fire for atrium with combustibles	5,000
Large fires	25,000

Table 3   Typical Fire Growth Times

t-Squared Fires	Growth Time t_g, s
Slow[a]	600
Medium[a]	300
Fast[a]	150
Ultrafast[b]	75

[a]Constants based on data from NFPA *Standards* 92B *and* 204.
[b]Constant based on data from Nelson (1987).

These unsteady fires are called ***t*-squared fires**; typical growth times are listed in Table 3.

Zone Fire Models

Atrium smoke management design is based on the zone fire model concept. This concept has been applied to several computer models used for atrium smoke management design analysis, including the Harvard Code (Mitler and Emmons 1981), ASET (Cooper 1985), the BRI Model (Tanaka 1983), CCFM (Cooper and Forney 1987), and CFAST (Peacock et al. 1993). The University of Maryland modified CCFM specifically for atrium smoke management design (Milke and Mowrer 1994). Although each of these models has unique features, they all share the same basic two-zone model concept.

For more information about zone models, see Mitler (1984), Mitler and Rockett (1986), and Quintiere (1989). The ASET-B model (Walton 1985) is a good starting point for learning about zone models.

Zone models were developed for room fires. In a room fire, hot gases rise above the fire, forming a **plume**. As the plume rises, it entrains air from the room so that the diameter and mass flow rate of the plume increase with elevation. Accordingly, plume temperature decreases with elevation. Fire gases from the plume flow up to the ceiling and form a hot stratified layer under the ceiling. Hot gases can flow through openings in walls to other spaces; this flow is referred to as a **door jet**, which is similar to a plume, except that it flows through an opening in a wall.

Figure 19A is a sketch of a room fire. Zone modeling is an idealization of the room fire conditions, as illustrated in Figure 19B. For this idealization, the temperatures of the hot upper and lower layers of the room are uniform. The height of the discontinuity between these layers is the same everywhere. The dynamic effects on pressure are considered negligible, so pressures are treated as hydrostatic. Other properties are considered uniform for each layer. Algebraic equations are used to calculate the mass flows caused by plumes and door jets.

Many computer zone models allow exhaust from the upper layer, which is essential for simulating atrium smoke exhaust systems. Heat transfer is estimated by methods ranging from a simple allowance as a fraction of the heat released by the fire to a complicated simulation including the effects of conduction, convection, and radiation.

Atrium Smoke Filling by a Steady Fire

The following experimental correlation of the accumulation of smoke in a space by a steady fire is the **steady-filling equation**:

$$\frac{z}{H} = 0.67 - 0.28 \ln\left(\frac{tq^{1/3}H^{-4/3}}{A/H^2}\right) \qquad (20)$$

where

    z = height of first indication of smoke above fire, ft
    H = ceiling height above fire, ft
    t = time, s
    q = heat release rate from steady fire, Btu/s
    A = cross-sectional area of atrium, ft^2

Equation (20) is conservative in that it estimates the height of the first indication of smoke above the fire rather than the smoke interface, as illustrated in Figure 20. In the idealized zone model, the smoke interface is considered to be a height where there is smoke above and none below. In actual fires, there is a gradual transition zone between the lower cool layer and upper hot layer. The first indication of smoke can be thought of as the bottom of the transition zone. Another factor making Equation (20) conservative is that it is based on a plume that has no contact with the walls, which would reduce entrainment of air.

Equation (20) is for a constant cross-sectional area with respect to height. For other atrium shapes, physical modeling or computational fluid dynamics (see Chapter 34 of the 2005 *ASHRAE Handbook—Fundamentals* for more information) can be used. Alternatively, a sensitivity analysis can be made using Equation (20) to set bounds on the filling time for an atrium of complex shape. The equation is appropriate for A/H^2 from 0.9 to 14 and for values of z greater than or equal to 20% of H. A value of z/H greater than 1 means that the smoke layer under the ceiling has not yet begun to descend. These conditions can be expressed as

$$A = \text{Constant with respect to } H$$

$$0.2 \le \frac{z}{H} < 1.0$$

$$0.9 \le \frac{A}{H^2} \le 14$$
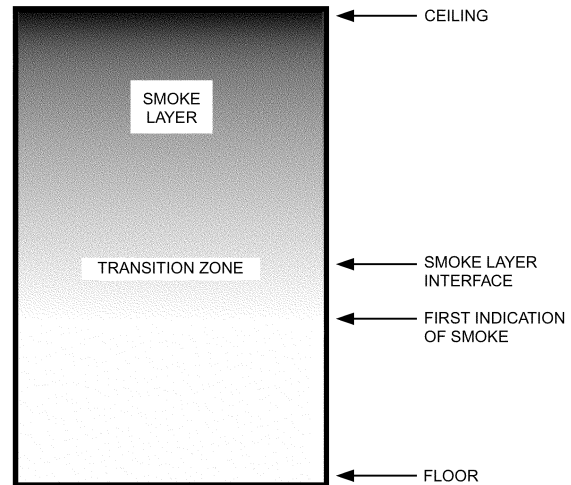
Fig. 20   Smoke Layer Interface

When Equation (20) is solved for z/H, z/H is often outside the acceptable range. Equation (20) can be solved for time.

$$t = \frac{A}{H^2} \times \frac{H^{4/3}}{q^{1/3}} \exp\left[\frac{1}{0.28}\left(0.67 - \frac{z}{H}\right)\right] \qquad (21)$$

Atrium Smoke Filling by an Unsteady Fire

To analyze atrium smoke filling with an unsteady fire, use zone fire or CFD models. Klote and Milke (2002) provide an algebraic equation for the smoke-filling time for an atrium with a *t*-squared fire, but this equation has limited applicability because *t*-squared fires can be extremely large for the times considered in many smoke-filling applications.

Steady Clear Height with Upper Layer Exhaust

Figure 18 illustrates smoke exhaust from the hot smoke layer at the top of an atrium to maintain a steady clear height. Smoke flow into the upper layer from the fire plume depends on the fire's heat release rate, clear height, fuel type, and fuel orientation. The following is a generalized plume approximation that does not take into account the specifics of the material being burned.

$$\dot{m} = 0.022 q_c^{1/3} z^{5/3} + 0.0042 q_c \qquad (22)$$

where

    $\dot{m}$ = mass flow of plume, lb$_m$/s
    q_c = convective heat release rate of fire, Btu/s
    z = clear height above top of fuel, ft

Clear height z is the distance from the top of the fuel to the interface between the "clear" space and the smoke layer. Because a smoke management system generally must protect against fire at any location, it is suggested that the top of the fuel be considered at the floor level.

Equation (22) is not applicable when the mean flame height is greater than the clear height. An approximate relationship for mean flame height is

$$z_f = 0.533 q_c^{2/5} \qquad (23)$$

where z_f = mean flame height, ft.

The convective portion q_c of the heat release rate can be expressed as

$$q_c = \xi q \qquad (24)$$
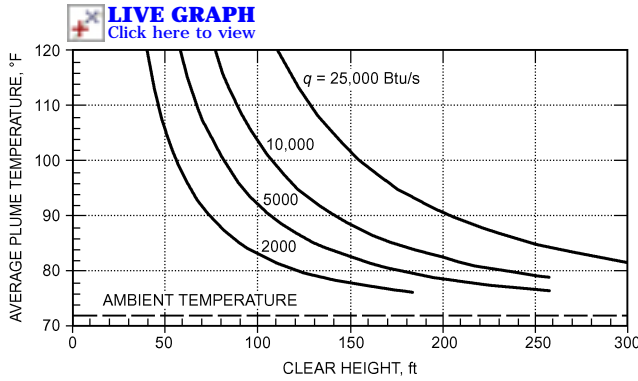
Note: Plume equations should not be used when plume temperature is less than 4°F above ambient.

Fig. 21 Average Plume Temperature

Fig. 22 Atrium Exhaust to Maintain Steady Clear Height

Fig. 23 Enlarged Scale for Figure 22

where ξ is the convective fraction of heat release. The convective fraction depends on the material being burned, heat conduction through the fuel, and the radiative heat transfer of the flames, but a value of 0.7 is often used.

The temperature of smoke entering the upper smoke layer is

$$T_p = T_a + \frac{q_c}{\dot{m} c_p} \tag{25}$$

where

T_p = plume temperature at clear height, °R
T_a = ambient temperature, °R
$\dot{m}$ = mass flow of plume, lb_m/s
q_c = convective heat release rate of fire, Btu/s
c_p = specific heat of plume gases, Btu/lb·°F

Figure 21 shows plume temperature as a function of height above the fuel as calculated from Equations (22) and (25). Smoke plumes consist primarily of air mixed with combustion products, and the specific heat of plume gases is generally taken to be the same as that of air (c_p = 0.24 Btu/lb·°F). Equation (22) was developed for strongly buoyant plumes. For small temperature differences between the plume and ambient, errors because of low buoyancy could be significant. This topic needs study, and, in the absence of better data, it is recommended that the plume equations not be used when this temperature difference is small (less than 4°F).

The density of smoke gases can be calculated from the perfect gas law:

$$\rho = \frac{p}{RT} \tag{26}$$

where

ρ = density, lb_m/ft³
p = absolute pressure, lb_f/ft²
R = gas constant, ft·lb_f/lb_m·°R
T = absolute temperature of smoke gases, °R

Volumetric flow is expressed as

$$Q = \frac{60 \dot{m}}{\rho} \tag{27}$$

where

$\dot{m}$ = mass flow of plume or exhaust air, lb_m/s
Q = volumetric flow of exhaust gases, cfm
ρ = density of plume or exhaust gases, lb_m/ft³

Atrium exhaust should equal the mass flow of the plume plus any leakage flow into the atrium above the clear height.

For an atrium with negligible heat loss from the smoke layer and negligible air leakage into the smoke layer from the outside, exhaust
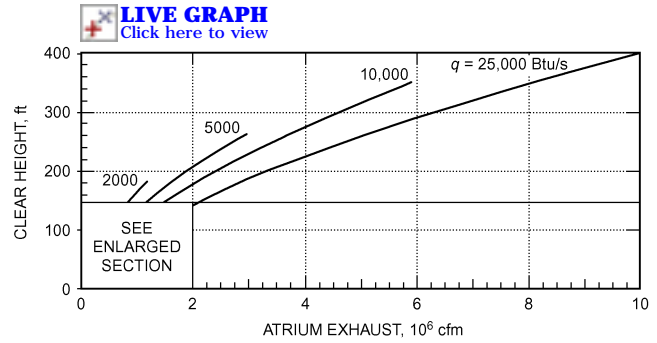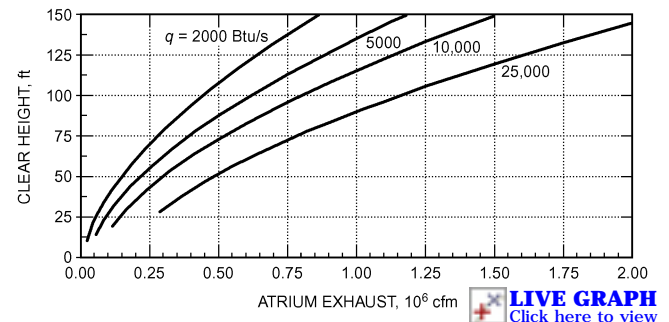
equals the plume's mass flow rate from Equation (22) at the same temperature as the plume from Equation (25). Figures 22 and 23 show the exhaust rate needed to maintain a constant clear height for an atrium with negligible heat loss from the smoke layer and negligible air leakage into the smoke layer from the outside.

The major assumptions of the analysis plotted in Figures 22 and 23 are as follows:

• Plume has space to flow to top of atrium without obstructions
• Heat release rate of fire is constant
• Clear height is greater than mean flame height
• Smoke layer is adiabatic
• Plume flow and exhaust are the only significant mass flows into or out of smoke layer (i.e., outside airflow, either as leakage or as makeup air, into smoke layer is insignificant)

Minimum Smoke Layer Depth

An atrium smoke management system must be designed with a smoke layer deep enough to accommodate a **ceiling jet**, a radial jet of smoke formed when a plume hits the ceiling. Usual estimates of ceiling jet depth are 10 to 20% of the distance between the base of the fuel and the ceiling (the ceiling jet itself is only about 10% of this distance, but at the walls the jet reverses and flows under itself). Generally, the smoke layer depth should be at least 20% of the distance between the base of the fuel and the ceiling.

Number of Exhaust Inlets

When the flow rate of a smoke exhaust inlet is relatively large, cold air from the lower layer can be pulled into the smoke exhaust. This phenomenon is called **plugholing**. A number of exhaust air inlets may be needed to prevent plugholing. The maximum volumetric flow rate that can be exhausted by a single exhaust inlet without plugholing is calculated by

$$V_{max} = 452 \gamma d^{5/2} \left(\frac{T_s - T_o}{T_o} \right)^{1/2} \tag{28}$$

where

V_{max} = maximum volumetric flow rate without plugholing at T_s, cfm
γ = exhaust location factor, dimensionless
d = depth of smoke layer below lowest point of exhaust inlet, ft
T_s = absolute temperature of smoke layer, °R
T_o = absolute ambient temperature, °R

The ratio d/D_i should be greater than 2 where D_i is the diameter of the of the exhaust inlet. For exhaust inlets centered no closer than $2D_i$ from the nearest wall, $\gamma = 1$ should be used; for less than $2D_i$, $\gamma = 0.5$ should be used. For exhaust inlets on a wall, use $\gamma = 0.5$.

For rectangular exhaust inlets, calculate D_i as

$$D_i = \frac{2ab}{a+b}$$

where

a = length of inlet
b = width of inlet

Where multiple inlets are needed to prevent plugholing, the minimum separation between inlets should be

$$S_{min} = 0.065 V_e^{1/2}$$

where

S_{min} = minimum edge-to-edge separation between inlets, ft
V_e = volumetric flow rate of one exhaust inlet, cfm

This approach for calculating V_{max} and S_{min} is consistent with that of NFPA *Standard* 92B. A less conservative approach was in earlier versions of this *Standard* and Klote and Milke (2002); research is needed to evaluate these approaches.

Separation Between Inlets

When exhaust at an inlet is near the maximum flow rate Q_{max}, adequate separation between exhaust inlets must be maintained to minimize interaction between flows near the inlets. One criterion for separation between inlets is that it be at least the distance from a single inlet that would result in an arbitrarily small velocity based on sink flow. Using 40 fpm as the arbitrary velocity, the minimum separation distance for inlets located in a wall near the ceiling (or in the ceiling near the wall) is

$$S_{min} = 0.023 \beta \sqrt{Q_e} \qquad (29)$$

where

S_{min} = minimum separation between inlets, ft
Q_e = volumetric flow rate, cfm
β = exhaust location factor, dimensionless

Prestratification and Detection

A layer of hot air often forms under the ceiling of an atrium because of solar radiation on the atrium roof. Although no studies have been made of this **prestratification layer**, building designers indicate that the temperature of such a layer can exceed 120°F. Temperatures below this layer are controlled by the building's heating and cooling system; the temperature can be considered to increase significantly over a small increase in elevation, as shown in Figure 24. The analysis of smoke stratification given in NFPA *Standard* 92B is not appropriate for the temperature profile addressed in this section because it is for a constant temperature increase per unit elevation.

When the average temperature of the plume is lower than that of the prestratification layer, the smoke will form a stratified layer beneath the prestratification layer, as shown in Figure 25. Average plume temperatures can be calculated from Equations (22) and (25); they are plotted in Figure 21, which shows that the average plume
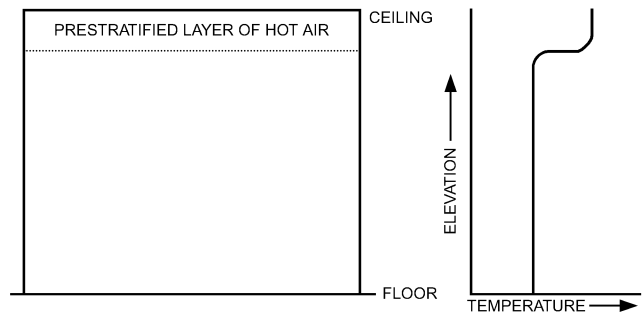
Note: Temperature below the hot layer is controlled by the building's heating and cooling system.

Fig. 24 Prestratified Layer of Hot Air under Atrium Ceiling and Resulting Temperature Profile
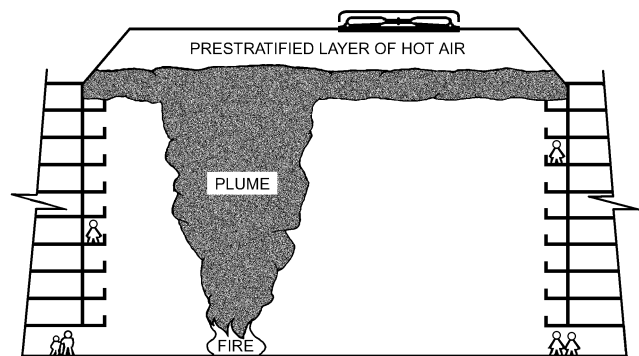
Fig. 25 Smoke Filling a Prestratified Atrium

temperature is usually less than expected temperatures of the hot air layer. Thus, when there is a prestratified layer, smoke cannot be expected to reach the atrium ceiling, and smoke detectors mounted on that ceiling cannot be expected to go into alarm.

Beam smoke detectors can overcome this detection difficulty. The following approaches can provide prompt detection regardless of air temperature under the ceiling when a fire begins:

• **Upward-Angled Beam to Detect Smoke Layer.** One or more beams are aimed upward to intersect the smoke layer regardless of the level of smoke stratification. For redundancy, more than one beam smoke detector is recommended. Advantages include not needing to locate several horizontal beams, and the minimized risk of false activation by sunlight (a risk with some beam smoke detectors) because the receivers are angled downward. Figure 26 illustrates the upward-angled beam approach.

• **Horizontal Beams at Various Levels to Detect Smoke Layer.** One or more beam detectors are located at roof level, with additional detectors at lower levels. Exact beam positioning depends on the specific design, but should include beams at the bottom of identified unconditioned spaces and at or near the design smoke level, with several beams at intermediate positions.

• **Horizontal Beams to Detect Smoke Plume.** Beams are arranged at a level below the lowest expected stratification level. These beams must be close enough to each other to ensure intersection of the plume; spacing should be based on the width of the beam at the least elevation above a point of fire potential.

All components of a beam smoke detector must be accessible for maintenance. For the arrangement shown in Figure 26, a roof opening (not shown) could provide access for maintenance.
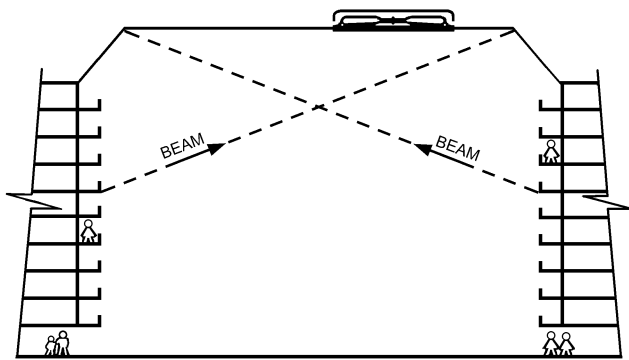
Fig. 26 Beam Detectors Used for Activation of Atrium Smoke Management System

TENABILITY SYSTEMS

The intent of smoke control systems is to provide a tenable environment in the means of egress or other locations during building fires. A **tenable environment** is one in which combustion products, including heat, are limited to a level that is not life threatening. Analysis of a tenability system consists of a smoke transport analysis and a tenability evaluation. For most applications, smoke transport calculations are done by either a computational fluid dynamic (CFD) model or a network model.

Tenability Evaluation

Tenability evaluation considers the effects of exposure to toxic gas, heat, and thermal radiation, as well as reduced visibility. Toxic gas, heat, and thermal radiation exposure are direct threats to life. The severity of each threat depends on the intensity and length of exposure.

Reduced visibility does not directly threaten life, but it is an indirect hazard. Reduced visibility can reduce walking speed. When occupants and firefighters cannot see very much, they often become disoriented and cannot get away from the smoke, thus prolonging their exposure. Another concern is that a disoriented person can fall from an atrium balcony, which can be fatal.

Considerable research has been conducted regarding tenability, and methods are available for calculating exposures to combustion gases and reduced visibility (ISO *Standard* 13571; Jin 2002; Klote and Milke 2002; Purser 2002). There is no broad consensus on visibility criteria, but Jin (2002) suggests 43 ft for applications where occupants are unfamiliar with the building (e.g., museums, casinos), and 13 ft when occupants are familiar with the building (e.g., residential applications). The U.K. Chartered Institution of Building Service Engineers (CIBSE 2003) suggests 26 to 33 ft.

When combustion products from most materials are diluted enough to meet any of these visibility criteria, the hazards to life from toxic gases, heat, and thermal radiation are also eliminated for exposures up to 20 min. This means that, for most fires, tenability can be evaluated by calculating visibility, if the hazards of other exposures are checked.

Atria and Other Large Spaces

For atria and other large spaces, it is appropriate to use a CFD model (see Chapter 34 of the 2005 *ASHRAE Handbook—Fundamentals* for CFD information) to calculate tenability. CFD has been used for a wide range of applications, including aircraft design, automotive design, boiler design, and weather forecasting, and is extensively used for atrium smoke management systems. For examples of CFD simulations of smoke transport in large spaces, see Hadjisophocleous et al. (1999), Kashef et al. (2002), Klote (2005), and Lougheed and Hadjisophocleous (2000).

The idea of CFD is to divide the space of interest into a large number of cells and to solve the governing equations for each cell. For atrium applications, the number of cells typically ranges from 100,000 to 1,000,000. Obstructions such as walls, balconies, and stairs need to be taken into account. Conditions at the boundaries need to be defined. Exhaust flow at or near the top of the atrium is specified, and makeup air conditions are also defined. This allows simulation of fluid flow in considerable detail.

Although CFD modeling has significant advantages in realistically simulating smoke flow, it is computationally intensive and requires a lot of computer memory and time; it is not uncommon for a CFD simulation to run for hours and sometimes days. Because CFD is computationally intensive, it produces so many numbers that the usual ways to evaluate computer output are inappropriate. Visualization methods have been developed so people can understand CFD results.

Several general-purpose CFD models are commercially available that can be used for atrium smoke control. The U.S. National Institute of Standards and Technology (NIST) developed the Fire Dynamics Simulator (FDS) model (McGrattan 2004; McGrattan and Forney 2004), and its visualization software called Smokeview (Forney and McGrattan 2004). The FDS model includes numerous fire-modeling applications, such as smoke plume flow, fires in enclosures, a burning townhouse, sprinklered fires, an oil tank fire, fires in aircraft hangars, rack storage commodity fire, and a brush fire advancing toward a house. FDS and Smokeview can be downloaded free of charge (www.fire.nist.gov/fds).

Large Multicompartmented Buildings

Because of the number of rooms and shafts in large multicompartmented buildings, it is often not feasible to use CFD to simulate smoke transport. Ideally, the model used for such simulations would be able to simulate a fire and mass and heat transfer throughout the building. No practical model can do this, but research is under way to develop such a model. Currently, the network model CONTAM is used to simulate smoke transport in large multicompartmented buildings. See the section on Computer Analysis for Pressurization Systems for more information about CONTAM. Ferreira (2002), Hadjisophocleous et al. (2002), Klote (2002, 2004), and Chapter 9 of Klote and Milke (2002) provide examples of tenability calculations using CONTAM. Because CONTAM requires that temperatures be supplied as data input by the user, the temperatures need to be calculated or estimated by the user.

ACCEPTANCE TESTING

Regardless of the care, skill, and attention to detail with which a smoke control system is designed, an acceptance test is needed as assurance that the system, as built, operates as intended.

An acceptance test should be composed of two levels of testing. The first is functional: an initial check of the system components. The importance of the initial check has become apparent because of problems encountered during tests of smoke control systems: fans operating backward, fans to which no electrical power was supplied, controls that did not work properly, etc.

The second level of testing is of performance, to determine whether the system performs adequately under all required modes of operation. This can consist of measuring pressure differences across barriers under various modes of smoke control system operation. If airflows through open doors are important, these should be measured. Chemical smoke from smoke candles (sometimes called smoke bombs) is not recommended for performance testing because it normally lacks the buoyancy of hot smoke from a real building fire. Smoke near a flaming fire has a temperature of 1000 to 2000°F. Heating chemical smoke to such temperatures to emulate smoke from a real fire is not recommended unless precautions are taken to protect life and property. The same comments about buoyancy apply to tracer gases. Thus, pressure-difference testing is the most

practical performance test. However, chemical smoke can be used to aid flow visualization.

ASHRAE *Guideline* 5 covers the commissioning of smoke management systems.

SPECIAL INSPECTOR

Some building codes require special inspection and tests of smoke control systems in addition to the ordinary inspection of and test requirements for buildings, structures, and parts of buildings. These special inspections and tests should verify the proper commissioning of the smoke control design in its final installed condition. Procedures for inspection and testing should be developed by the smoke control system's special inspector, with approval of the authorities having jurisdiction. The special inspector needs to understand the principles of smoke control, including code requirements. The special inspector should check that the components of the system are as specified and that those components are installed as intended, as well as whether the smoke control system performs as intended.

EXTRAORDINARY INCIDENTS

Extraordinary incidents, whether caused by war, terrorism, accident, or natural disaster, can affect immediate human needs such as survival and safety, and also longer-term needs such as air, water, food, and shelter. Some buildings are designed with specific features intended to make them less susceptible to extraordinary incidents. It is recommended that actuation of systems for fire and smoke protection be of higher priority than possibly conflicting automatic strategies designed to respond to other extraordinary conditions.

Some acts of terrorism use fire, and those using bombs often lead to fires. It is well known that war, terrorist attacks, and natural disasters have the potential to disrupt utilities and interfere with fire fighting, and this often permits any fires that occur to grow unchecked. For these reasons, simultaneous fire and other extraordinary incidents should be considered likely, and any features intended to mitigate extraordinary conditions should be designed accordingly. For more information, see ASHRAE's (2003) report, *Risk Management Guidance for Health, Safety and Environmental Security under Extraordinary Incidents* and Chapter 58 of this volume.

SYMBOLS

A = area, ft^2
a = dilution rate, air changes per minute
A_{bo} = flow area between building and outside (per floor), ft^2
A_f = area of floor, ft^2
A_{sb} = flow area between stairwell and building (per floor), ft^2
A_w = area of wall, ft^2
B = $7.64(1/T_o - 1/T_s)$ at sea level standard pressure
C = concentration of contaminant at initial time θ; flow coefficient
C_o = initial concentration of contaminant
c_p = specific heat of plume gases, Btu/lb·°F
C_w = pressure coefficient, dimensionless
d = distance from doorknob to edge of knob side of door, ft
e = base of natural logarithm (approximately 2.718)
F = total door-opening force, lb_f
F_{dc} = force to overcome door closer, lb_f
i = floor-to-ceiling height, or ceiling height above fire, ft
H_j = thickness of ceiling jet, ft
h = distance above neutral plane, ft
$\dot{m}$ = mass flow of plume or exhaust air, lb_m/s
i = number of floors
p = absolute pressure, lb_f/ft^2
p_w = pressure exerted by wind, in. of water
Q = volumetric flow rate, cfm
q = heat release rate of fire, Btu/s

q_c = heat release rate, Btu/h or Btu/s
Q_e = volumetric flow rate, cfm
Q_{in} = volumetric flow rate of air into fire compartment, cfm
Q_{out} = volumetric flow rate of smoke out of fire compartment, cfm
R = gas constant, $ft·lb_f·/lb_m·°R$
S_{min} = minimum separation between inlets, ft
T = absolute temperature of smoke gases, °R
t = time, min or s
T_a = ambient temperature, °R
T_f = average absolute temperature of fire compartment, °R
t_g = growth time, s
T_i = absolute temperature of air inside shaft, °R
T_{in} = absolute temperature of air into fire compartment, °R
T_j = absolute temperature of ceiling jet, °R
T_o = absolute temperature of outside air, °R
T_{out} = absolute temperature of smoke leaving fire compartment, °R
T_p = plume temperature at clear height, °R
T_s = absolute temperature of stairwell air or surroundings, °R
V = wind velocity, mph
V_k = critical air velocity to prevent smoke backflow, fpm
W = corridor or door width, ft
y = distance above stairwell bottom, ft
z = height of first indication of smoke above fire, or clear height above top of fuel, ft
z_f = mean flame height, ft

Greek

β = exhaust location factor, dimensionless
Δp = pressure difference, in. of water
Δp_{sb} = pressure difference between stairwell and building, in. of water
Δp_{sbb} = pressure difference between stairwell and building at stairwell bottom, in. of water
Δp_{sbt} = pressure difference from stairwell to building at stairwell top, in. of water
θ = time
ρ = density, lb_m/ft^3
ρ_o = outside air density, lb_m/ft^3
ξ = convective fraction of heat release

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CHAPTER 53

RADIANT HEATING AND COOLING

RADIANT heating and cooling applications are classified as panel heating or cooling if the panel surface temperature is below 300°F, and as low-, medium-, or high-intensity radiant heating if the surface or source temperature exceeds 300°F. In thermal radiation heat is transferred by electromagnetic waves that travel in straight lines, and can be reflected. Thermal radiation principally occurs between surfaces or between a source and a surface. In a conditioned space, air is not heated or cooled in this process. Because of these characteristics, radiant systems are effective for both spot heating and space heating or cooling requirements for an entire building.

Sensible heating loads may be reduced by 4 to 16% compared to ASHRAE standard design load. Percent reduction increases with the air change rate (Suryanarayana and Howell 1990).

LOW-, MEDIUM-, AND HIGH-INTENSITY INFRARED HEATING

Low-, medium-, and high-intensity infrared heaters are compact, self-contained direct-heating devices used in hangars, warehouses, factories, greenhouses, and gymnasiums, as well as in areas such as loading docks, racetrack stands, outdoor restaurants, animal breeding areas, swimming pool lounge areas, and areas under marquees. Infrared heating is also used for snow melting and freeze protection (e.g., on stairs and ramps) and process heating (e.g., paint baking and drying). An infrared heater may be electric, gas-fired, or oil-fired and is classified by the source temperature as follows:

• Low-intensity (source temperatures to 1200°F)
• Medium-intensity (source temperatures to 1800°F)
• High-intensity (source temperatures to 5000°F)

The source temperature is determined by such factors as the source of energy, the configuration, and the size. Reflectors can be used to direct the distribution of thermal radiation in specific patterns. Chapter 15 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment* covers radiant equipment in detail.

PANEL HEATING AND COOLING

Panel heating and cooling systems provide a comfortable environment by controlling surface temperatures and minimizing air motion within a space. They include the following designs:

• Ceiling panels
• Embedded hydronic tubing or attached piping in ceilings, walls, or floors
• Air-heated or cooled floors or ceilings
• Electric ceiling or wall panels
• Electric heating cable or wire mats in ceilings or floors
• Deep heat, a modified storage system using electric heating cable or embedded hydronic tubing in ceilings or floors

In these systems, generally more than 50% of the heat transfer between the temperature-controlled surface and other surfaces is by thermal radiation. Panel heating and cooling systems are used in residences, office buildings, classrooms, hospital patient rooms, swimming pool areas, repair garages, and in industrial and warehouse applications. Additional information is available in Chapter 6 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*.

Some radiant panel systems, referred to as hybrid HVAC systems, combine radiant heating and cooling with central air conditioning (Scheatzle 2003). They are used more for cooling than for heating (Wilkins and Kosonen 1992). The controlled-temperature surfaces may be in the floor, walls, or ceiling, with temperature maintained by electric resistance or circulation of water or air. The central station can be a basic, one-zone, constant-temperature, or constant-volume system, or it can incorporate some or all the features of dual-duct, reheat, multizone, or variable-volume systems. When used in combination with other water/air systems, radiant panels provide zone control of temperature and humidity.

Metal ceiling panels may be integrated into the central heating and cooling system to provide individual room or zone heating and cooling. These panels can be designed as small units to fit the building module, or they can be arranged as large continuous areas for economy. Room thermal conditions are maintained primarily by direct transfer of radiant energy, normally using four-pipe hot and chilled water. These systems have generally been used in hospital patient rooms. Metal ceiling panel systems are discussed in Chapter 6 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*.

ELEMENTARY DESIGN RELATIONSHIPS

When considering radiant heating or cooling for human comfort, the following terms describe the temperature and energy characteristics of the total radiant environment:

• **Mean radiant temperature** (MRT) $\bar{t}_r$ is the temperature of an imaginary isothermal black enclosure in which an occupant would exchange the same amount of heat by radiation as in the actual nonuniform environment.
• **Ambient temperature** t_a is the temperature of the air surrounding the occupant.
• **Operative temperature** t_o is the temperature of a uniform isothermal black enclosure in which the occupant would exchange the same amount of heat by radiation and convection as in the actual nonuniform environment.

For air velocities less than 80 fpm and mean radiant temperatures less than 120°F, the operative temperature is approximately equal to the adjusted dry-bulb temperature, which is the average of the air and mean radiant temperatures.
• **Adjusted dry-bulb temperature** is the average of the air temperature and the mean radiant temperature at a given location. The adjusted dry-bulb temperature is approximately equivalent to the operative temperature for air motions less than 80 fpm and mean radiant temperatures less than 120°F.

The preparation of this chapter is assigned to TC 6.5, Radiant and Convective Space Heating and Cooling.

53.1

- **Effective radiant flux** (ERF) is defined as the net radiant heat exchanged at ambient temperature t_a between an occupant, whose surface is hypothetical, and all enclosing surfaces and directional heat sources and sinks. Thus, ERF is the net radiant energy received by the occupant from all surfaces and sources whose temperatures *differ* from t_a. ERF is particularly useful in high-intensity radiant heating applications.

The relationship between these terms can be shown for an occupant at surface temperature t_{sf}, exchanging sensible heat H_m in a room with ambient air temperature t_a and mean radiant temperature $\bar{t}_r$. The linear radiative and convective heat transfer coefficients are h_r and h_c, respectively; the latter is a function of the relative movement between the occupant and air movement V. The heat balance equation is

$$H_m = h_r(t_{sf} - \bar{t}_r) + h_c(t_{sf} - t_a) \tag{1}$$

During thermal equilibrium, H_m is equal to metabolic heat minus work and evaporative cooling by sweating. By definition of operative temperature,

$$H_m = (h_r + h_c)(t_{sf} - t_o) = h(t_{sf} - t_o) \tag{2}$$

The combined heat transfer coefficient is h, where $h = h_r + h_c$. Using Equations (1) and (2) to solve for t_o yields

$$t_o = \frac{h_r \bar{t}_r + h_c t_a}{h_r + h_c} = t_a + \left(\frac{h_r}{h}\right)(\bar{t}_r - t_a) \tag{3}$$

Thus, t_o is an average of $\bar{t}_r$ and t_a, weighted by their respective heat transfer coefficients; it represents how people sense the thermal level of their total environment as a single temperature.

Rearranging Equation (1) and substituting $h - h_r$ for h_c,

$$H_m + h_r(\bar{t}_r - t_a) = h(t_{sf} - t_a) \tag{4}$$

where $h_r(\bar{t}_r - t_a)$ is, by definition, the effective radiant flux (ERF) and represents the radiant energy absorbed by the occupant from all sources whose temperatures differ from t_a.

The principal relationships between $\bar{t}_r$, t_a, t_o, and ERF are as follows:

$$ERF = h_r(\bar{t}_r - t_a) \tag{5}$$

$$ERF = h(t_o - t_a) \tag{6}$$

$$\bar{t}_r = t_a + ERF/h_r \tag{7}$$

$$t_o = t_a + ERF/h \tag{8}$$

$$\bar{t}_r = t_a + (h/h_r)(t_o - t_a) \tag{9}$$

$$t_o = t_a + (h_r/h)(\bar{t}_r - t_a) \tag{10}$$

In Equations (1) to (10), the radiant environment is treated as a blackbody with temperature $\bar{t}_r$. The effect of the emittance of the source, radiating at absolute temperature in degrees Rankine, and the absorptance of skin and clothed surfaces is reflected in the effective values of $\bar{t}_r$ or ERF and not in h_r, which is generally given by

$$h_r = 4\sigma f_{eff} \left[\frac{(\bar{t}_r + t_a)}{2} + 460\right]^3 \tag{11}$$

where

    h_r = linear radiative heat transfer coefficient, Btu/h·ft²·°F
    f_{eff} = ratio of radiating surface of the human body to its total DuBois surface area $A_D = 0.71$
    σ = Stefan-Boltzmann constant = 0.1712×10^{-8} Btu/h·ft²·°R⁴

The convective heat transfer coefficient for an occupant depends on the relative velocity between the occupant and the surrounding air, as well as the occupant's activity:

- If the occupant is walking in still air,

$$h_c = 0.092V^{0.53} \qquad \{100 < V < 400 \text{ fpm}\} \tag{12a}$$

where V is the occupant's walking speed.
- If the occupant is sedentary with moving air,

$$h_c = 0.061V_a^{0.6} \qquad \{40 < V_a < 800 \text{ fpm}\} \tag{12b}$$

$$h_c = 0.55 \qquad \{0 < V_a < 40 \text{ fpm}\} \tag{12c}$$

More information about h_c may be found in Chapter 8 of the 2005 *ASHRAE Handbook—Fundamentals*.

When $\bar{t}_r > t_a$, ERF adds heat to the body; when $t_a > \bar{t}_r$, heat is lost from the body because of thermal radiation. ERF is independent of the occupant's surface temperature and can be measured directly by a black globe thermometer or any blackbody radiometer or flux meter using the ambient air t_a as its heat sink.

In these definitions and for radiators below 1700°F (2160°R), the body clothing and skin surface are treated as blackbodies, exchanging radiation with an imaginary blackbody surface at temperature $\bar{t}_r$. The effectiveness of a radiating source on human occupants is governed by the absorptance α of the skin and clothing surface for the color temperature (in °R) of that radiating source. The relationship between α and temperature is illustrated in Figure 1. Values for α are those expected relative to the matte black surface normally found on globe thermometers or radiometers measuring radiant energy. A gas radiator usually operates at 1700°F (2160°R); a quartz lamp, for example, radiates at 4000°F (4460°R) with 240 V; and the sun's radiating temperature is 10,000°F (10,460°R). The use of α in estimating the ERF and t_o caused by sources radiating at temperatures above 1700°F (2160°R) is discussed in the section on Testing Instruments for Radiant Heating.
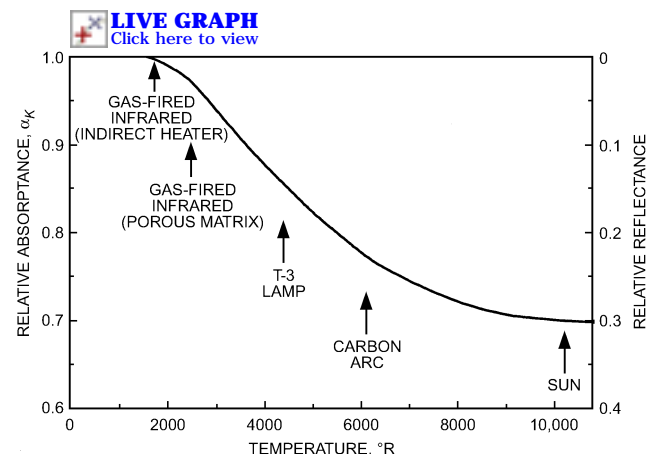
Fig. 1   Relative Absorptance and Reflectance of Skin and Typical Clothing Surfaces at Various Color Temperatures
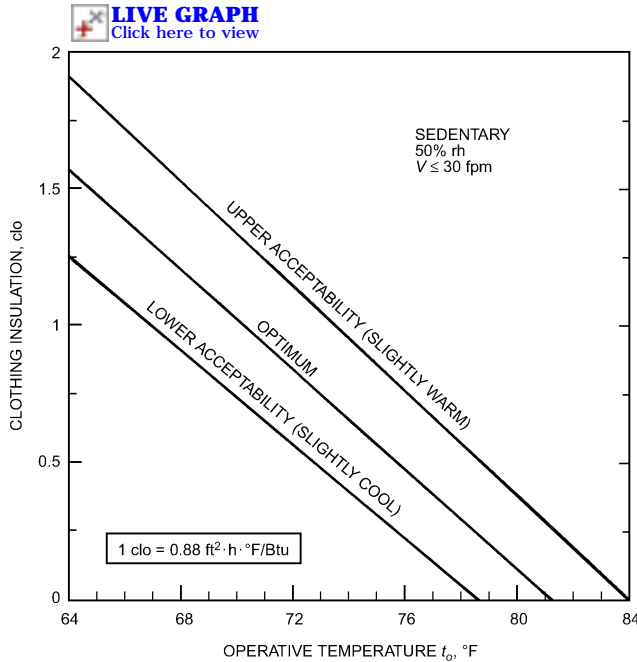
Fig. 2 Range of Thermal Acceptability for Sedentary People with Various Clothing Insulations and Operative Temperatures

Notes: [a]1 clo = 0.880 ft^2·h·°F/Btu; [b]1 met = 18.4 Btu/h·ft^2

Fig. 3 Optimum Operative Temperatures for Active People in Low-Air-Movement Environments

DESIGN CRITERIA FOR ACCEPTABLE RADIANT HEATING

Perceptions of comfort, temperature, and thermal acceptability are related to activity, body heat transfer from the skin to the environment, and the resulting physiological adjustments and body temperature. The split between convective and radiant heat transfer from or to a body is also a matter of subjective human comfort. The optimum split is about 60% by thermal radiation and 40% by thermal convection. Heat transfer is affected by ambient air temperature, thermal radiation, air movement, humidity, and clothing worn. Thermal sensation is described as feelings of hot, warm, slightly warm, neutral, slightly cool, cool, and cold. An acceptable environment is defined as one in which at least 80% of the occupants perceive a thermal sensation between "slightly cool" and "slightly warm." Comfort is associated with a neutral thermal sensation during which the human body regulates its internal temperature with minimal physiological effort for the activity concerned. In contrast, warm discomfort is primarily related to the physiological strain necessary to maintain the body's thermal equilibrium rather than to the temperature sensation experienced. For a full discussion of the interrelation of physical, psychological, and physiological factors, refer to Chapter 8 of the 2005 *ASHRAE Handbook—Fundamentals*.

ANSI/ASHRAE *Standard* 55-1992 shows a linear relationship between clothing insulation worn and the operative temperature t_o for comfort (Figure 2). Figure 3 shows the effect of both activity and clothing on the t_o for comfort. Figure 4 shows the slight effect humidity has on the comfort of a sedentary person wearing average clothing. Figures 2, 3, and 4 are adapted from ANSI/ASHRAE *Standard* 55, Thermal Environmental Conditions for Human Occupancy.

A comfortable t_o at 50% rh is perceived as slightly warmer as humidity increases, or as slightly cooler as humidity decreases. Changes in humidity have a much greater effect on warm and hot discomfort. In contrast, cold discomfort is only slightly affected by humidity and is very closely related to a cold thermal sensation.

Determining the specifications for a radiant heating installation designed for human occupancy and acceptability involves the following steps:
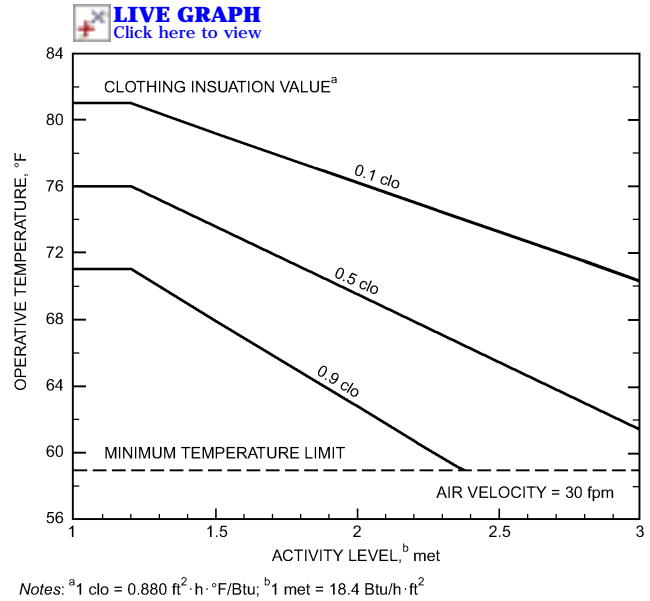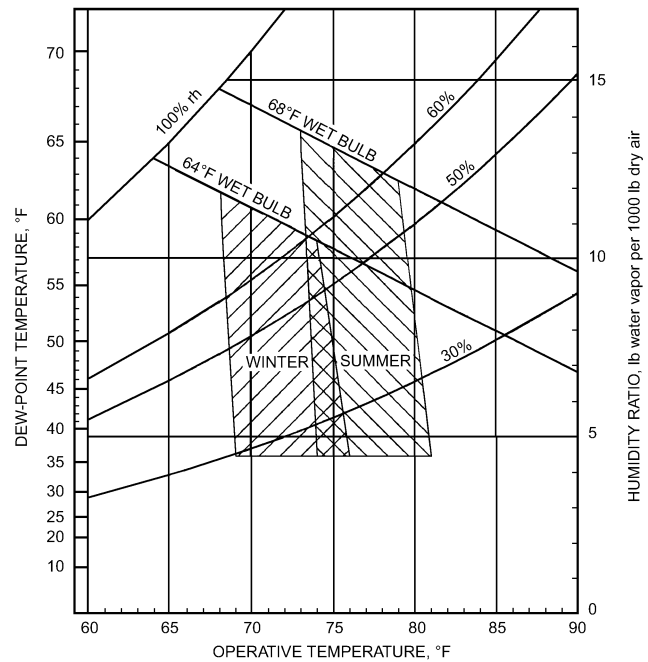
Fig. 4 ASHRAE Comfort Chart for Sedentary Occupants

1. Define the probable activity (metabolism) level of, and clothing worn by, the occupant and the relative air velocity. The following are two examples:

Case 1: Sedentary (1.1 met)
Clothing insulation = 0.6 clo; V = 30 fpm
Case 2: Light work (walking) (2 met)
Clothing insulation = 0.9 clo; V = 100 fpm

2. From Figure 2 (sedentary) or 3 (active), determine the optimum t_o for comfort and acceptability:

$$\textit{Case } 1: t_o = 75°F; \quad \textit{Case } 2: t_o = 62.5°F$$

3. For ambient air temperature t_a, calculate the mean radiant temperature $\bar{t}_r$ and/or ERF necessary for comfort and thermal acceptability.

Case 1: For $t_a = 60°F$ and 50% rh and assuming $\bar{t}_r = 86°F$,
    Solve for h_r from Equation (11):

$$h_r = 4 \times 0.1712 \times 10^{-8} \times 0.71[(86 + 60)/2 + 460]^3 = 0.736$$

    Solve for h_c from Equation (12c):

$$h_c = 0.55$$

Then,

$$h = h_r + h_c = 0.736 + 0.55 = 1.286 \text{ Btu/h·ft}^2·°F$$

$$\frac{h_r}{h} = \frac{0.736}{1.286} = 0.57$$

From Equation (6), for comfort,

$$\text{ERF} = 1.286(75 - 60) = 19.3 \text{ Btu/h·ft}^2$$

From Equation (9),

$$\bar{t}_r = 60 + (1.286/0.736)(75 - 60) = 86.2°F$$

Case 2: For $t_a = 50°F$ and assuming $\bar{t}_r = 81°F$,

$$h_r = 4 \times 0.1712 \times 10^{-8} \times 0.71[(81 + 50)/2 + 460]^3 = 0.706$$

$$h_c = 0.092(100)^{0.53} = 1.06$$

$$h = 0.706 + 1.06 = 1.766 \text{ Btu/h·ft}^2·°F$$

$$\frac{h_r}{h} = \frac{0.706}{1.766} = 0.40$$

$$\text{ERF} = 1.766(62.5 - 50) = 22.1 \text{ Btu/h·ft}^2$$

From Equation (7),

$$\bar{t}_r = 50 + 22.1/0.706 = 81.3°F$$

The t_o for comfort, predicted by Figure 2, is on the cool side when the humidity is low; for high humidities, the predicted t_o for comfort is warm. This effect on comfort for sedentary occupants can be seen in Figure 4. For example, for high humidity at $t_{dp} = 59°F$, the t_o for comfort is

Case 1: $t_o = 73.5°F$, compared to 75°F at 50% rh

When thermal acceptability is the primary consideration in an installation, humidity can sometimes be ignored in preliminary design specifications. However, for conditions where radiant heating and the work level cause sweating and high heat stress, humidity is a major consideration and a hybrid HVAC system should be used.

Equations (3) to (12) can also be used to determine the ambient air temperature t_a required when the mean radiant temperature MRT is maintained by a specified radiant system.

When calculating heat loss, t_a must be determined. For a radiant system that is to maintain a MRT of $\bar{t}_r$, the operative temperature t_o can be determined from Figure 4. Then, t_a can be calculated by recalling that t_o is approximately equal to the average of t_a and t_r. For example, for a t_o of 73°F and a radiant system designed to maintain an MRT of 78°F, the t_a would be 68°F.
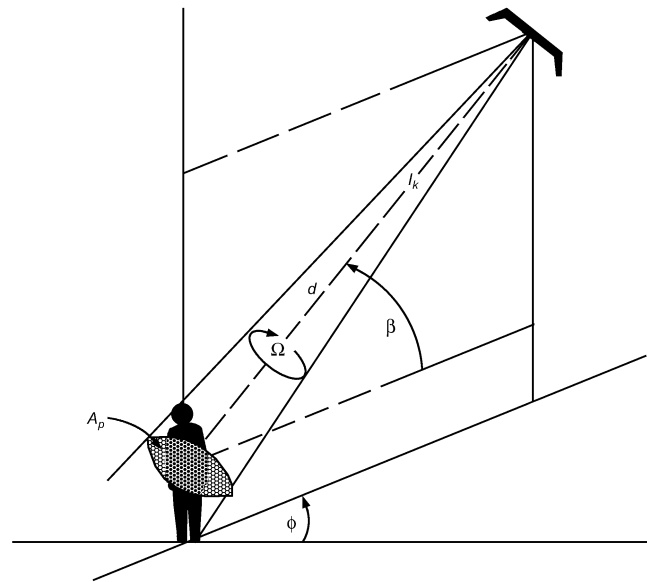
Fig. 5   Geometry and Symbols for Describing Beam Heaters

When the surface temperature of outside walls, particularly those with large areas of glass, deviates too much from room air temperature and from the temperature of other surfaces, simplified calculations for load and operative temperature may lead to errors in sizing and locating the panels. In such cases, more detailed radiant exchange calculations may be required, with separate estimation of heat exchange between the panels and each surface. A large window area may lead to significantly lower MRTs than expected. For example, Athienitis and Dale (1987) reported an MRT 5.4°F lower than room air temperature for a room with a glass area equivalent to 22% of its floor area.

DESIGN FOR BEAM RADIANT HEATING

Spot beam radiant heat can improve comfort at a specific location in a large, poorly heated work area. The design problem is specifying the type, capacity, and orientation of the beam heater.

Using the same reasoning as in Equations (1) to (10), the effective radiant flux ΔERF added to an unheated work space with an operative temperature t_{uo} to result in a t_o for comfort (as given by Figure 2 or 3) is

$$\Delta\text{ERF} = h(t_o - t_{uo}) \tag{13}$$

or

$$t_o = t_{uo} + \Delta\text{ERF}/h \tag{14}$$

The heat transfer coefficient h for the occupant in Equation (13) is given by Equations (11) and (12), with $h = h_r + h_c$.

By definition, ERF is the energy absorbed per unit of total body surface A_D (DuBois area) and *not* the total effective radiating area A_{eff} of the body.

Geometry of Beam Heating

Figure 5 illustrates the following parameters that must be considered in specifying a beam radiant heater designed to produce the ERF, or mean radiant temperature $\bar{t}_r$, necessary for comfort at an occupant's workstation:

Ω = solid angle of heater beam, steradians (sr)
I_K = irradiance from beam heater, Btu/h·sr
K = subscript for absolute temperature of beam heater, °R
β = elevation angle of heater, degrees (at 0°, beam is horizontal)
φ = azimuth angle of heater, degrees (at 0°, beam is facing subject)

d = distance from beam heater to center of occupant, ft
A_p = projected area of occupant on a plane normal to direction of heater beam (ϕ, β), ft^2
α_K = absorptance of skin-clothing surface at emitter temperature (see Figure 1)

ERF may also be measured as the heat absorbed at the occupant's clothing and skin surface from a beam heater at absolute temperature:

$$\mathrm{ERF} = \frac{\alpha_K I_K A_p}{d^2 A_D} \qquad (15)$$

where ERF is in Btu/h·ft^2 and (A_p/d^2) is the solid angle subtended by the projected area of the occupant from the radiating beam heater I_K, which is treated here as a point source. A_D is the DuBois area:

$$A_D = 0.0621 W^{0.425} H^{0.725}$$

where

W = occupant weight, lb
H = occupant height, ft

For additional information on radiant flux distribution patterns and sample calculations of radiation intensity I_K and ERF, refer to Chapter 15 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*.

Floor Reradiation

In most low-, medium-, and high-intensity radiant heater installations, local floor areas are strongly irradiated. The floor absorbs most of this energy and warms to an equilibrium temperature t_f, which is higher than the ambient air temperature t_a and the unheated room enclosure surfaces. Part of the energy directly absorbed by the floor is transmitted by conduction to the colder layers beneath (or, for slabs-on-grade, to the ground), part is transferred by natural convection to room air, and the rest is reradiated. The warmer floor will raise ERF or $\bar{t}_r$ over that caused by the heater alone.

For a person standing on a large, flat floor that has a temperature raised by direct radiation t_f, the linearized $\bar{t}_r$ due to the floor and unheated walls is

$$\bar{t}_{rf} = F_{p-f} t_f + (1 - F_{p-f}) t_a \qquad (16)$$

where the unheated walls, ceiling, and ambient air are assumed to be at t_a, and F_{p-f} is the angle factor governing radiation exchange between the heated floor and the person.

The ERF$_f$ from the floor affecting the occupant, which is due to the $(t_f - t_a)$ difference, is

$$\begin{aligned}\mathrm{ERF}_f &= h_r(\bar{t}_{rf} - t_a) \\ &= h_r F_{p-f}(t_f - t_a)\end{aligned} \qquad (17)$$

where h_r is the linear radiative heat transfer coefficient for a person as given by Equation (11). For a standing or sitting subject when the walls are farther than 16 ft away, F_{p-f} is 0.44 (Fanger 1973). For an average-sized 16 by 16 ft room, a value of 0.35 for F_{p-f} is suggested. For detailed information on floor reradiation, see Chapter 15 in the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*.

In summary, when radiant heaters warm occupants in a selected area of a poorly heated space, the radiation heat necessary for comfort consists of two additive components: (1) ERF directly caused by the heater and (2) reradiation ERF$_f$ from the floor. The effectiveness of floor reradiation can be improved by choosing flooring with a low specific conductivity. Flooring with high thermal inertia may be desirable during radiant transients, which may occur as heaters are cycled by a thermostat set to the desired operative temperature t_o.

Asymmetric Radiant Fields

In the past, comfort heating has required flux distribution in occupied areas to be uniform, which is not possible with beam radiant heaters. Asymmetric radiation fields, such as those experienced when lying in the sun on a cool day or when standing in front of a warm fire, can be pleasant. Therefore, a limited amount of asymmetry, which is allowable for comfort heating, is referred to as "reasonable uniform radiation distribution" and is used as a design requirement.

To develop criteria for judging the degree of asymmetry allowable for comfort heating, Fanger et al. (1980) proposed defining radiant temperature asymmetry as the difference in the plane radiant temperature between two opposing surfaces. Plane radiant temperature is the equivalent $\bar{t}_{r1}$ caused by radiation on one side of the subject, compared with the equivalent $\bar{t}_{r2}$ caused by radiation on the opposite side. Gagge et al. (1967) conducted a study of subjects (eight clothed and eight unclothed) seated in a chair and heated by two lamps. Unclothed subjects found a $(\bar{t}_r - t_a)$ asymmetry as high as 20°F to be comfortable, but clothed subjects were comfortable with an asymmetry as high as 31°F.

For an unclothed subject lying on an insulated bed under a horizontal bank of lamps, neutral temperature sensation occurred for a t_o of 72°F, which corresponds to a $(t_o - t_a)$ asymmetry of 20°F or a $(\bar{t}_r - t_a)$ asymmetry of 27°F, both averaged for eight subjects (Stevens et al. 1969). In studies of heated ceilings, 80% of eight male and eight female clothed subjects voted conditions as comfortable and acceptable for asymmetries as high as 20°F. The study compared the floor and heated ceilings. Asymmetry in the MRTs for direct radiation from three lamps and for floor reradiation is about 1°F, which is negligible.

In general, the human body has a great ability to sum sensations from many hot and cold sources. For example, a study of Australian aborigines sleeping unclothed next to open fires in the desert at night found a t_a of 43°F (Scholander 1958). The $\bar{t}_r$ caused directly by three fires was 171°F, and the sky $\bar{t}_r$ was 30°F; the resulting t_o was 82°F, which is acceptable for human comfort.

According to the limited field and laboratory data available, an allowable design radiant asymmetry of 22 ± 5°F should cause little discomfort over the comfortable t_o range used by ASHRAE *Standard* 55 and in Figures 2 and 3. Increased clothing insulation allows increases in the acceptable asymmetry, but increased air movement reduces it. Increased activity also reduces human sensitivity to changing $\bar{t}_r$ or t_o and, consequently, increases the allowable asymmetry. The design engineer should use caution with an asymmetry greater than 27°F, as measured by a direct beam radiometer or estimated by calculation.

RADIATION PATTERNS

Figure 6 indicates basic radiation patterns commonly used in design for radiation from point or line sources (Boyd 1962). A point source radiates over an area proportional to the square of the distance from the source. The area for a (short) line source also varies substantially as the square of the distance, with about the same area as the circle actually radiated at that distance. For line sources, the pattern width is determined by the reflector shape and position of the element within the reflector. The rectangular area used for installation purposes as the pattern of radiation from a line source assumes a length equal to the width plus the fixture length. This assumed length is satisfactory for design, but is often two or three times the pattern width.

Electric infrared fixtures are often identified by their beam pattern (Rapp and Gagge 1967), which is the radiation distribution normal to the line source element. The beam of a high-intensity infrared

A. PATTERN OF RADIATION FROM POINT SOURCE

B. PATTERN OF RADIATION FROM LINE SOURCE
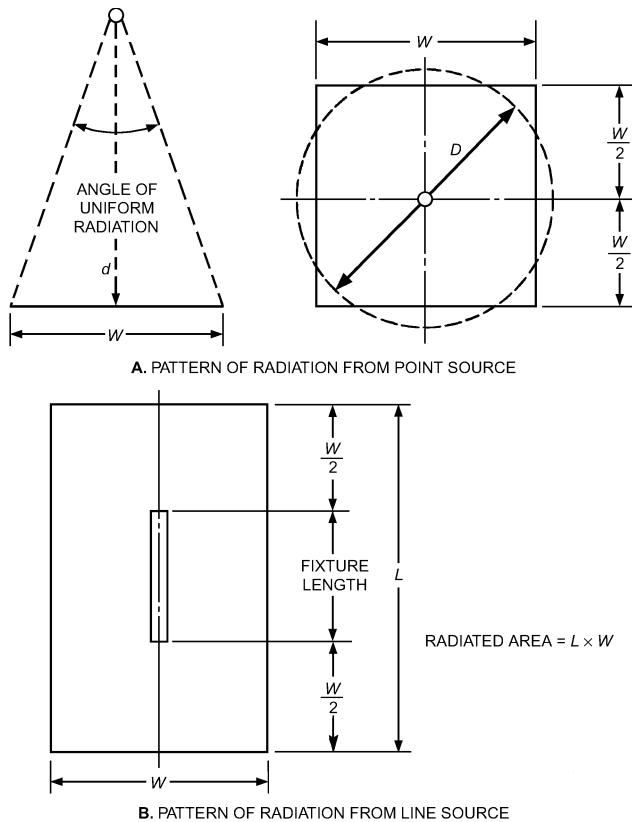
Note: The projected area W^2 normal to a beam that is Ω steradians wide at distance d is Ωd^2. The floor area irradiated by a beam heater at an angle elevation β is $W^2/\sin\beta$. Fixture length L increases the area irradiated by $(1 + L/W)$.

Fig. 6   Basic Radiation Patterns for System Design
(Boyd 1962)

fixture may be defined as that area in which the intensity is at least 80% of the maximum intensity encountered anywhere within the beam. This intensity is measured in the plane in which maximum control of energy distribution is exercised.

The beam size is usually designated in angular degrees and may be symmetrical or asymmetrical in shape. For adaptation to their design specifications, some manufacturers indicate beam characteristics based on 50% maximum intensity.

The control used for an electric system affects the desirable maximum end-to-end fixture spacing. Actual pattern length is about three times the design pattern length, so control in three equal stages is achieved by placing every third fixture on the same circuit. If all fixtures are controlled by input controllers or variable voltage to electric units, end-to-end fixture spacing can be nearly three times the design pattern length. Side-to-side minimum spacing is determined by the fixture's distribution pattern and is not influenced by the control method.

Low-intensity equipment typically consists of a steel tube hung near the ceiling and parallel to the outside wall. Circulation of combustion products inside the tube elevates the tube temperature, and radiant energy is emitted. The tube is normally provided with a reflector to direct the radiant energy down into the space to be conditioned.

Radiant ceiling panels for heating only are installed with spacing between them to enhance downward convection, and are usually the primary heat source for the space. Usually the source is a surface. Details of radiant and convective heat transfer for panel heating and cooling are given in Chapter 6 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*. Flux density is inversely proportional to distance from the source if the source is a recessed line, and
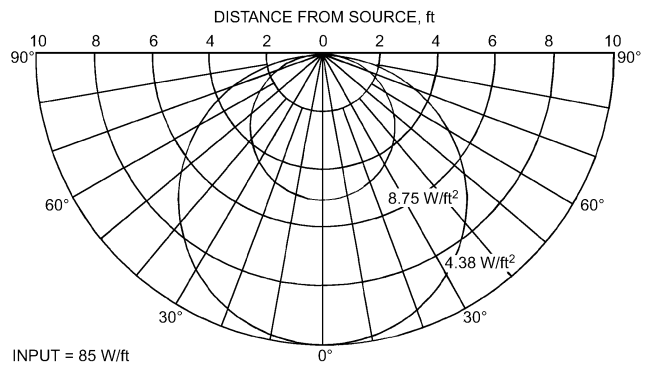
Fig. 7   Lines of Constant Radiant Flux for a Line Source

is inversely proportional to the square of the distance from the source if the source is a point. In practice, actual dependence will be between these limits.

The rate of radiation exchange between a panel and a particular object depends on their temperatures, surface emittances, and geometrical orientation (i.e., shape factor). It also depends on the temperatures and configurations of all the other objects and walls within the space.

The heat flux for an ideal line source is shown in Figure 7. All objects (except the radiant source) are at the same temperature, and the radiant source is suspended symmetrically in the room.

DESIGN FOR TOTAL SPACE HEATING

Radiant heating differs from conventional heating by a moderately elevated ERF, $\bar{t}_r$, or t_o over ambient temperature t_a. Standard methods of design are normally used, although informal studies indicate that radiant heating results in a lower heating load than convection heating (Zmeureanu et al. 1987). Buckley and Seel (1987) demonstrated that a combination of elevated floor temperature, higher mean radiant temperature, and reduced ambient temperature results in lower thermostat settings, reduced temperature differential across the building envelope, and thus lower heat loss and heating load for the structure. In addition, peak load may be decreased because of heat (cool) stored in the structure when embedded panels in the floor, walls, or ceiling are used (Kilkis 1992).

Most gas radiation systems for full-building heating concentrate the bulk of capacity at mounting heights of 10 to 16 ft at the perimeter, directed at the floor near the walls. Units can be mounted considerably higher. Successful application depends on supplying the proper amount of heat in the occupied area. Heaters should be located to take maximum advantage of the radiation pattern produced. Exceptions to perimeter placement include walls with high transmission losses and extreme height, as well as large roof areas where roof heat losses exceed perimeter and other heat losses.

Electric infrared systems installed indoors for complete building heating use layouts that uniformly distribute the radiation throughout the area used by people, as well as layouts that emphasize perimeter placement, such as in ice hockey rinks. Some electric radiant heaters emit significant visible radiation and provide both heating and illumination.

The orientation of equipment and people is less important for general area heating (large areas within larger areas) than for spot heating. With reasonably uniform radiation distribution in work or living areas, the exact orientation of the units is not important. Higher intensities of radiation may be desirable near walls with outside exposure. Radiation shields (reflective to infrared) fastened a few inches from the wall to allow free air circulation between the wall and shield are effective for frequently occupied work locations close to outside walls.

In full-building heating, units should be placed where their radiant and convective output best compensates for the structure's heat loss. The objective of a complete heating system is to provide a warm floor with low conductance to the heat sink beneath the floor. This thermal storage may permit cycling of units with standard controls.

TESTING INSTRUMENTS FOR RADIANT HEATING

In designing a radiant heating system, calculation of radiant heat exchange may involve some untested assumptions. During field installation, the designer must test and adjust the equipment to ensure that it provides acceptable comfort conditions. The black globe thermometer and directional radiometer can be used to evaluate the installation.

Black Globe Thermometer

The classic (Bedford) globe thermometer is a thin-walled, matte black, hollow sphere with a thermocouple, thermistor, or thermometer placed at the center. It can directly measure $\bar{t}_r$, ERF, and t_o. When a black globe is in thermal equilibrium with its environment, the gain in radiant heat from various sources is balanced by the convective loss to ambient air. Thus, in terms of the globe's linear radiative and convective heat transfer coefficients, h_{rg} and h_{cg}, respectively, the heat balance at equilibrium is

$$h_{rg}(\bar{t}_{rg} - t_g) = h_{cg}(t_g - t_a) \tag{18}$$

where $\bar{t}_{rg}$ is the mean radiant temperature measured by the globe and t_g is the temperature in the globe.

In general, the $\bar{t}_{rg}$ of Equation (18) equals the $\bar{t}_r$ affecting a person when the globe is placed at the center of the occupied space and when the radiant sources are distant from the globe.

The effective radiant flux measured by a black globe is

$$ERF_g = h_{rg}(\bar{t}_{rg} - t_a) \tag{19}$$

which is analogous to Equation (5) for occupants. From Equations (18) and (19), it follows that

$$ERF_g = (h_{rg} + h_{cg})(t_g - t_a) \tag{20}$$

If the ERF_g of Equation (20) is modified by the skin-clothing absorptance α_K and the shape f_{eff} of an occupant relative to the black globe, the corresponding ERF affecting the occupant is

$$ERF \text{ (for an occupant)} = f_{eff}\alpha_K ERF_g \tag{21}$$

where α_K is defined in the section on Geometry of Beam Heating and f_{eff}, which is defined after Equation (11), is approximately 0.71 and equals the ratio h_r/h_{rg}. The t_o affecting an occupant, in terms of t_g and t_a, is given by

$$t_o = Kt_g + (1 - K)t_a \tag{22}$$

where the coefficient K is

$$K = \alpha_K f_{eff}(h_{rg} + h_{cg})/(h_r + h_c) \tag{23}$$

Ideally, when K is unity, the t_g of the globe would equal the t_o affecting an occupant.

For an average comfortable equilibrium temperature of 77°F and noting that f_{eff} for the globe is unity, Equation (11) yields

$$h_{rg} = 1.06 \text{ Btu}/(\text{h·ft}^2 \cdot °\text{F}) \tag{24}$$

and Equation (12) yields

Table 1　Value of K for Various Air Velocities and Globe Thermometer Diameters ($\alpha_g = 1$)

Air Velocity V_a, fpm	Approximate Globe Thermometer Diameter D, in.			
	2	**4**	**6**	**8**
50	1.35	1.15	1.05	0.99
100	1.43	1.18	1.06	0.99
200	1.49	1.21	1.07	1.00
400	1.54	1.23	1.08	1.00
800	1.59	1.26	1.09	1.00

$$h_{cg} = 0.296D^{-0.4}V_2^{0.53} \qquad \{100 \text{ fpm} < V_a < 400 \text{ fpm}\} \tag{25}$$

where

　D = globe diameter, in.
　V_a = air velocity, fpm

Equation (25) is Bedford's convective heat transfer coefficient for a 6 in.globe's convective loss, modified for D. For any radiating source below1700°F, the ideal diameter of a sphere that makes $K = 1$ that is independent of air movement is 8 in. (see Table 1). Table 1 shows the value of K for various values of globe diameter D and ambient air movement V. The table shows that the uncorrected temperature of the traditional 6 in. globe would overestimate the true $(t_o - t_a)$ difference by 6% for velocities up to 200 fpm, and the probable error of overestimating t_o by t_g uncorrected would be less than 0.9°F. Globe diameters between 6 and 8 in. are optimum for using the uncorrected t_g measurement for t_o. The exact value for K may be used for smaller globes when estimating t_o from t_g and t_a measurements. The value of $\bar{t}_r$ may be found by substituting Equations (24) and (25) in Equation (18), because $\bar{t}_r$ (occupant) is equal to $\bar{t}_{rg}$. The smaller the globe, the greater the variation in K caused by air movement. Globes with D greater than 8 in. will overestimate the importance of radiation gain versus convection loss.

For sources radiating at high temperatures (1300 to 10,000°F), the ratio α_m/α_g may be set near unity by using a pink-colored globe surface, whose absorptance for the sun is 0.7, a value similar to that of human skin and normal clothing (Madsen 1976).

In summary, the black globe thermometer is simple and inexpensive and may be used to determine $\bar{t}_r$ [Equation (18)] and the ERF [Figure 1 and Equations (20) and (21)]. When the radiant heater temperature is less than 1700°F, the uncorrected t_g of a 6 to 8 in. black globe is a good estimate of the t_o affecting the occupants. A pink globe extends its usefulness to sun temperatures (10,000°F). A globe with a low mass and low thermal capacity is more useful because it reaches thermal equilibrium in less time.

Using the heat exchange principles described, many heated and unheated instruments of various shapes have been designed to measure acceptability in terms of t_o, $\bar{t}_r$, and ERF, as sensed by their own geometric shapes. Madsen (1976) developed an instrument that can determine the predicted mean vote (PMV) from the $(t_g - t_a)$ difference, as well as correct for clothing insulation, air movement, and activity (ISO 1994).

Directional Radiometer

The angle of acceptance (in steradians) in commercial radiometers allows the engineer to point the radiometer directly at a wall, floor, or high-temperature source and read the average temperature of that surface. Directional radiometers are calibrated to measure either the radiant flux accepted by the radiometer or the equivalent blackbody radiation temperature of the emitting surface. Many radiometers collimate (make parallel) input to sense small areas of body, clothing, wall, or floor surfaces. A directional radiometer allows rapid surveys and analyses of important radiant heating factors such as the temperature of skin, clothing surfaces, and walls and floors, as well as the radiation intensity I_K of heaters on the occupants. One

radiometer for direct measurement of the equivalent radiant temperature has an angle of acceptance of 2.8° or 0.098 sr, so that at 1 ft, it measures the average temperature over a projected circle about 3/8 in. in diameter.

APPLICATIONS

When installing radiant heaters in specific applications, consider the following factors:

- Gas and electric high-temperature infrared heaters must not be placed where they could ignite flammable dust or vapors, or decompose vapors into toxic gases.
- Fixtures must be located with recommended clearances to ensure proper heat distribution. Stored materials must be kept far enough from fixtures to avoid hot spots. Manufacturers' recommendations must be followed.
- Unvented gas heaters inside tight, poorly insulated buildings may cause excessive humidity with condensation on cold surfaces. Proper insulation, vapor barriers, and ventilation prevent these problems.
- Combustion heaters in tight buildings may require makeup air to ensure proper venting of combustion gases. Some infrared heaters are equipped with induced-draft fans to relieve this problem.
- Some transparent materials may break because of uneven application of high-intensity infrared. Infrared energy is transmitted without loss from the radiator to the absorbing surfaces. The system must produce the proper temperature distribution at the absorbing surfaces. Problems are rarely encountered with glass 0.25 in. or less in thickness.
- Comfort heating with infrared heaters requires a reasonably uniform heat flux distribution in the occupied area. Although thermal discomfort can be relieved in warm areas with high air velocity, such as on loading docks, the full effectiveness of a radiant-heater installation is reduced by high air velocity.
- Radiant spot heating and zoning in large undivided areas with variable occupancy patterns provides localized heating just where and when people are working, which reduces the heating cost.

By building periodic microstructure into a thin silicon carbide wafer, infrared panel surfaces that are highly directional and coherent over many wavelengths can be obtained (Greffet et al. 2002).

Low-, Medium-, and High-Intensity Infrared Applications

Low-, medium-, and high-intensity infrared equipment is used extensively in industrial, commercial, and military applications. This equipment is particularly effective in large areas with high ceilings, such as in buildings with large air volumes and in areas with high infiltration rates, large access doors, or large ventilation requirements.

Factories. Low-intensity radiant equipment suspended near the ceiling around the perimeter of facilities with high ceilings enhances the comfort of employees because it warms floors and equipment in the work area. For older, uninsulated buildings, the energy cost for low-intensity radiant equipment is less than that of other heating systems. High-intensity infrared for spot heating and low-intensity infrared for zone temperature control effectively heat large unheated facilities.

Warehouses. Low- and high-intensity infrared are used for heating warehouses, which usually have a large volume of air, poor insulation, and high infiltration. Low-intensity infrared equipment is installed near the ceiling around the building's perimeter. High-level mounting near the ceiling leaves floor space available for product storage. Both low- and high-intensity infrared are arranged to control radiant intensity and provide uniform heating at the working level and frost protection areas, which is essential for perishable goods storage.

Garages. Low-intensity infrared provides comfort for mechanics working near or on the floor. With elevated MRT in the work area, comfort is provided at a lower ambient temperature.

In winter, opening the large overhead doors to admit equipment for service allows a substantial entry of cold outdoor air. On closing the doors, the combination of reradiation from the warm floor and radiant heat warming the occupants (not the air) provides rapid recovery of comfort. Radiant energy rapidly warms the cold vehicles. Radiant floor panel heating systems are also effective.

Low-intensity equipment is suspended near the ceiling around the perimeter, often with greater concentration near overhead doors. High-intensity equipment is also used to provide additional heat near doors.

Aircraft Hangars. Equipment suspended near the roofs of hangars, which have high ceilings and large access doors, provides uniform radiant intensity throughout the working area. A heated floor is particularly effective in restoring comfort after an aircraft has been admitted. As in garages, the combination of reradiation from the warm floor and radiation from the radiant heating system provides rapid regain of comfort. Radiant energy also heats aircraft moved into the work area.

Greenhouses. In greenhouse applications, a uniform flux density must be maintained throughout the facility to provide acceptable growing conditions. In a typical application, low-intensity units are suspended near, and run parallel to, the peak of the greenhouse.

Sometimes the soil is warmed by embedding pipes in the ground. The same system may also contribute to sensible heating of the greenhouse.

Outdoor Applications. Applications include loading docks, racetrack stands, outdoor restaurants, and under marquees. Low-, medium-, and high-intensity infrared are used in these facilities, depending on their layout and requirements.

Other Applications. Radiant heat may be used in a variety of large facilities with high ceilings, including religious compounds, day-care facilities, gymnasiums, swimming pools, enclosed stadiums, and facilities that are open to the outdoors. Radiant energy is also used to control condensation on surfaces such as large glass exposures. Careful sizing and design of direct gas-fired systems may improve thermal comfort in places of assembly by affecting air and wall surface temperatures. A numerical study with computational fluid design (CFD) models may be essential to achieve these benefits and reduce condensation risk (Xiang et al. 2001).

Low-, medium-, and high-intensity infrared are also used for other industrial applications, including process heating for component or paint drying ovens, humidity control for corrosive metal storage, and snow control and freeze-protection for parking or loading areas.

Panel Heating and Cooling

Residences. Embedded pipe systems, electric resistance panels, and forced warm-air panel systems have all been used in residences. The embedded pipe system is most common, using plastic or rubber tubing in the floor slab or copper tubing in older plaster ceilings. These systems are suitable for conventionally constructed residences with normal amounts of glass. Lightweight hydronic metal panel ceiling systems have also been applied to residences, and prefabricated electric panels are advantageous, particularly in rooms that have been added on.

Office Buildings. A panel system is usually applied as a perimeter heating system. Panels are typically piped to provide exposure control with one riser on each exposure and all horizontal piping incorporated in the panel piping. In these applications, the air system provides individual room control. Perimeter radiant panel systems have also been installed with individual zone controls. However, this type of installation is usually more expensive and, at best, provides minimal energy savings and limited additional occupant comfort. Radiant panels can be used for cooling as well

as heating. Cooling installations are generally limited to retrofit or renovation jobs where ceiling space is insufficient for the required duct sizes. In these installations, the central air supply system provides ventilation air, dehumidification, and some sensible cooling. Two- and four-pipe water distribution systems may be used. Hot-water supply temperatures are commonly reset by outside temperature, with additional offset or flow control to compensate for solar load. Panel systems are readily adaptable to accommodate most changes in partitioning. Electric panels in lay-in ceilings have been used for full perimeter heating.

Schools. In all areas except gymnasiums and auditoriums, panels are usually selected for heating only, and may be used with any type of approved ventilation system. The panel system is usually sized to offset the transmission loads plus any reheating of the air. If the school is air conditioned by a central air system and has perimeter heating panels, single-zone piping may be used to control the panel heating output, and the room thermostat modulates the supply air temperature or volume. Heating and cooling panel applications are similar to those in office buildings. Panel heating and cooling for classroom areas has no mechanical equipment noise to interfere with instructional activities.

Hospitals. The principal application of heating and cooling radiant panels has been for hospital patient rooms. Perimeter radiant heating panels are typically applied in other areas of hospitals. Compared to conventional systems, radiant heating and cooling systems are well suited to hospital patient rooms because they (1) provide a draft-free, thermally stable environment, (2) have no mechanical equipment or bacteria and virus collectors, and (3) do not take up space in the room. Individual room control is usually achieved by throttling the water flow through the panel. The supply air system is often 100% outdoor air; minimum air quantities delivered to the room are those required for ventilation and exhaust of the toilet room and soiled linen closet. The piping system is typically a four-pipe design. Water control valves should be installed in corridors so that they can be adjusted or serviced without entering patient rooms. All piping connections above the ceiling should be soldered or welded and thoroughly tested. If cubicle tracks are applied to the ceiling surface, track installation should be coordinated with the radiant ceiling. In panel cooling, surface condensation may need a separate latent system (Isoardi and Brasselet 1995). Security panel ceilings are often used in areas occupied by mentally disturbed patients so that equipment cannot be damaged by a patient or used to inflict injury.

Swimming Pools. A partially clothed person emerging from a pool is very sensitive to the thermal environment. Panel heating systems are well suited to swimming pool areas. Floor panel temperatures must be controlled so they do not cause foot discomfort. Ceiling panels are generally located around the perimeter of the pool, not directly over the water. Panel surface temperatures are higher to compensate for the increased ceiling height and to produce a greater radiant effect on partially clothed bodies. Ceiling panels may also be placed over windows to reduce condensation.

Apartment Buildings. For heating, pipe coils are embedded in the masonry slab. The coils must be carefully positioned so as not to overheat one apartment while maintaining the desired temperature in another. The slow response of embedded pipe coils in buildings with large glass areas may be unsatisfactory. Installations for heating and cooling have been made with pipes embedded in hung plaster ceilings. A separate minimum-volume dehumidified air system provides the necessary dehumidification and ventilation for each apartment. The application of electric resistance elements embedded in floors or behind a skim coat of plaster at the ceiling has increased. Electric panels are easy to install and simplify individual room control.

Industrial Applications. Panel systems are widely used for general space conditioning of industrial buildings in Europe (Petras 2001). For example, the walls and ceilings of an internal combustion engine test cell are cooled with chilled water. Although the ambient air temperature in the space reaches up to 95°F, the occupants work

in relative comfort when 55°F water is circulated through the ceiling and wall panels.

Other Buildings. Metal panel ceiling systems can be operated as heating systems at elevated water temperatures and have been used in airport terminals, convention halls, lobbies, and museums, especially those with large glass areas. Cooling may also be applied. Because radiant energy travels through the air without warming it, ceilings can be installed at any height and remain effective. One particularly high ceiling installed for a comfort application is 50 ft above the floor, with a panel surface temperature of approximately 285°F for heating. The ceiling panels offset the heat loss from a single-glazed, all-glass wall.

The high lighting levels in television studios make them well suited to panels that are installed for cooling only and are placed above lighting to absorb the radiation and convection heat from the lights and normal heat gains from the space. The panel ceiling also improves the acoustical properties of the studio.

Metal panel ceiling systems are also installed in minimum- and medium-security jail cells and in facilities where disturbed occupants are housed. The ceiling is strengthened by increasing the gage of the ceiling panels, and security clips are installed so that the ceiling panels cannot be removed. Part of the perforated metal ceiling can be used for air distribution.

District Energy Systems. Panel heating and cooling increases the thermal efficiency and use rate of low-enthalpy energy resources like waste heat. Buildings equipped with panels may be cascaded with buildings with high-enthalpy HVAC systems, which increases the use rate of district energy systems (Kilkis 2002).

New Techniques. The introduction of thermoplastic and rubber tubing and new design techniques have improved radiant panel heating and cooling equipment. The systems are energy-efficient and use low water temperatures available from solar collectors and heat pumps (Kilkis 1993). Metal radiant panels can be integrated into ceiling design to provide a narrow band of radiant heating around the building perimeter. These new radiant systems are more attractive, provide more comfortable conditions, operate more efficiently, and have a longer life than some baseboard or overhead air systems.

SYMBOLS

A_D = total DuBois surface area of person, ft^2

A_{eff} = effective radiating area of person, ft^2

A_p = projected area of occupant normal to the beam, ft^2

clo = unit of clothing insulation equal to 0.880 $\text{ft}^2 \cdot °F \cdot h/Btu$

D = diameter of globe thermometer, in.

d = distance of beam heater from occupant, ft

ERF = effective radiant flux (person), $\text{Btu/h} \cdot \text{ft}^2$

ERF_f = radiant flux caused by heated floor on occupant, $\text{Btu/h} \cdot \text{ft}^2$

ERF_g = effective radiant flux (globe), $\text{Btu/h} \cdot \text{ft}^2$

F_{p-f} = angle factor between occupant and heated floor

f_{eff} = ratio of radiating surface (person) to its total area (DuBois)

H_m = net metabolic heat loss from body surface, $\text{Btu/h} \cdot \text{ft}^2$

h = combined heat transfer coefficient (person), $\text{Btu/h} \cdot \text{ft}^2 \cdot °F$

h_c = convective heat transfer coefficient for person, $\text{Btu/h} \cdot \text{ft}^2 \cdot °F$

h_{cg} = convective heat transfer coefficient for globe, $\text{Btu/h} \cdot \text{ft}^2 \cdot °F$

h_r = linear radiative heat transfer coefficient (person), $\text{Btu/h} \cdot \text{ft}^2 \cdot °F$

h_{rg} = linear radiative heat transfer coefficient for globe, $\text{Btu/h} \cdot \text{ft}^2 \cdot °F$

I_K = irradiance from beam heater, $\text{Btu/h} \cdot \text{sr}$

K = coefficient that relates t_a and t_g to t_o [Equation (22)]

K = subscript indicating absolute temperature of beam heater, °R

L = fixture length, ft

met = unit of metabolic energy equal to 18.4 $\text{Btu/h} \cdot \text{ft}^2$

t_a = ambient air temperature near occupant, °F

t_f = floor surface temperature, °F

t_g = globe temperature, °F

t_o = operative temperature, °F

$\bar{t}_r$ = mean radiant temperature affecting occupant, °F

$\bar{t}_{rf}$ = linearized $\bar{t}_r$ caused by floor and unheated walls on occupant, °F

t_{sf} = exposed surface temperature of occupant, °F

t_{uo} = operative temperature of unheated workspace, °F

V = relative velocity between occupant and air, fpm

V_a = air velocity, fpm

W = width of a square equivalent to the projected area of a beam of angle Ω steradians at a distance d, ft

α = relative absorptance of skin-clothing surface to that of matte black surface

α_g = absorptance of globe

α_K = absorptance of skin-clothing surface at emitter temperature

α_m = absorptance of skin-clothing surface at emitter temperatures above 1700°F

β = elevation angle of beam heater, degrees

σ = Stefan-Boltzmann constant = 0.1712×10^{-8} Btu/h·ft^2·°R^4

ϕ = azimuth angle of heater, degrees

Ω = radiant beam width, sr

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CHAPTER 54

SEISMIC AND WIND RESTRAINT DESIGN

ALMOST all inhabited areas of the world are susceptible to the damaging effects of either earthquakes or wind. Restraints that are designed to resist one may not be adequate to resist the other. Consequently, when exposure to either earthquake or wind loading is a possibility, strength of equipment and attachments should be evaluated for all appropriate conditions.

Earthquake damage to inadequately restrained HVAC&R equipment can be extensive. Mechanical equipment that is blown off the support structure can become a projectile, threatening life and property. The cost of properly restraining the equipment is small compared to the high costs of replacing or repairing damaged equipment, or compared to the cost of building downtime due to damaged facilities.

Design and installation of seismic and wind restraints has the following primary objectives:

• To reduce the possibility of injury and the threat to life.
• To reduce long-term costs due to equipment damage and resultant downtime.

Note: The intent of building codes with respect to seismic design is not to prevent damage to property or the restrained equipment itself.

This chapter covers the design of restraints to limit equipment movement and to keep the equipment captive during an earthquake or extreme wind loading. Seismic restraints and isolators do not reduce the forces transmitted to the restrained equipment. Instead, properly designed and installed seismic restraints and isolators have the necessary strength to withstand the imposed forces. However, equipment that is to be restrained must also have the necessary strength to remain attached to the restraint. Equipment manufacturers should review structural aspects of the design in the areas of attachment to ensure the equipment will remain attached to the restraint.

For mechanical systems, analysis of seismic and wind loading conditions is typically a static analysis, and conservative safety factors are applied to reduce the complexity of earthquake and wind loading response analysis and evaluation. The following three aspects are considered in a properly designed restraint system:

• *Attachment of equipment to restraint.* The equipment must be positively attached to the restraint, and must have sufficient strength to withstand the imposed forces, and to transfer the forces to the restraint.
• *Restraint design.* The restraint also must be strong enough to withstand the imposed forces. This should be determined by the manufacturer by tests and/or analysis.
• *Attachment of restraint to substructure.* Attachment may be by bolts, welds, or concrete anchors. The substructure must be capable of surviving the imposed forces.

The preparation of this chapter is assigned to TC 2.7, Seismic and Wind Restraint Design.

SEISMIC RESTRAINT DESIGN

Most seismic requirements adopted by local jurisdictions in North America are based on model codes developed by the International Conference of Building Officials (ICBO), Building Officials and Code Administrators International (BOCA), the Southern Building Code Conference, Inc. (SBCCI), and the National Building Code of Canada (NBCC), or on the requirements of the National Earthquake Hazards Reduction Program (NEHRP). The model code bodies, working through the International Code Council (ICC), have unified their model codes into the International Building Code (IBC). Local building officials must be contacted for specific requirements that may be more stringent than those presented in this chapter.

Other sources of seismic restraint information include

• *Seismic Restraint Manual: Guidelines for Mechanical Systems*, published by SMACNA (1998), includes seismic restraint information for mechanical equipment subjected to seismic forces of up to 1.0*g*.
• The National Fire Protection Association (NFPA) standards on restraint design are the same as those in the IBC.
• U.S. Department of Energy DOE 430.1A and ASME AG-1 cover restraint design for nuclear facilities.
• *Technical Manual* TM 5-809-10, published by the U.S. Army, Navy, and Air Force (1992), also provides guidance for seismic restraint design.
• *A Practical Guide to Seismic Restraint* [ASHRAE Research Project RP-812 (2000)], covers a broad range of seismic restraint design issues.

In seismically active areas where governmental agencies regulate the earthquake-resistive design of buildings (e.g., California), the HVAC engineer usually does not prepare the code-required seismic restraint calculations. The HVAC engineer selects the heating and cooling equipment and, with the assistance of the acoustical engineer (if the project has one), selects the required vibration isolation devices. The HVAC engineer specifies these devices and calls for shop drawing submittals from the contractors, but the manufacturer employs a registered engineer to design and detail the installation. The HVAC engineer reviews the shop design and details the installation, reviews the shop drawings and calculations, and obtains the approval of the architect and structural engineer before issuance to the contractors for installation.

To ensure that the proper design factors are used, a responsible source on the project team must provide information on the seismic design conditions (zone, soil type, etc. as applicable) to the engineer evaluating the installation.

Anchors for tanks, brackets, and other equipment supports that do not require vibration isolation may be designed by the building's structural engineer or by the supplier of the seismic restraints (depending on contractual arrangements between design team

members), based on layout drawings prepared by the HVAC engineer. The building officials maintain the code-required quality control over the design by requiring that all building design professionals are registered (licensed) engineers. Upon completion of installation, the supplier of the seismic restraints, or a qualified representative, should inspect the installation and verify that all restraints are installed properly and comply with specifications.

TERMINOLOGY

Base plate thickness. Thickness of the equipment bracket fastened to the floor.

Effective shear force V_{eff}. Maximum shear force of one seismic restraint or tie-down bolt.

Effective tension force T_{eff}. Maximum tension force or pullout force on one seismic restraint or tie-down bolt.

Equipment. Any HVAC&R component that must be restrained from movement during an earthquake.

Fragility level. Maximum lateral acceleration force that the equipment is able to withstand. These data may be available from the equipment manufacturer and are generally on the order of four times the acceleration of gravity ($4g$) for mechanical equipment.

Resilient support. An active seismic device (such as a spring with a bumper) to prevent equipment from moving more than a specified amount.

Response spectra. Relationship between the acceleration response of the ground and the peak acceleration of the earthquake in a damped single degree of freedom at various frequencies. The ground motion response spectrum varies with soil conditions.

Rigid support. Passive seismic device used to restrict any movement.

Shear force V. Force generated at the plane of the seismic restraints, acting to cut the restraint at the base.

Seismic restraint. Device designed to withstand seismic forces and hold equipment in place during an earthquake.

Seismic force levels. The geographic location of a facility determines its seismic zone, as given in the Uniform Building Code or International Building Code.

Snubber. Device made of steel-housed resilient bushings arranged to prevent equipment from moving beyond an established gap.

Tension force T. Force generated by overturning moments at the plane of the seismic restraints, acting to pull out the bolt.

CALCULATIONS

Sample calculations presented here assume that the equipment support is an integrated resilient support and restraint device. When the two functions of resilient support and motion restraint are separate or act separately, additional spring loads may need to be added to the anchor load calculation for the restraint device. Internal loads within integrated devices are not addressed in this chapter. These devices must be designed to withstand the full anchorage loads plus any internal spring loads.

Both static and dynamic analyses reduce the force generated by an earthquake to an equivalent statically applied force, which acts in a horizontal or vertical direction at the component's center of gravity. The resulting overturning moment is resisted by shear and tension (pullout) forces on the tie-down bolts. Static analysis is used for both rigidly mounted and resiliently mounted equipment.

Dynamic Analysis

Dynamic analysis of the isolation and snubber systems may be based on ground-level response spectra given in both IBC 2000 and IBC 2003, or NFPA Code 5000 (referenced in SEI/ASCE *Standard* 7-02) can be used as input for a dynamic analysis. Upper-level response spectra can be found in ATC 29-2 or ICC-ES (2007). Site-specific ground response spectra developed by a geotechnical or soils engineer may be used, as well. The computer analysis used

Table 1 Minimum Fragility Level Guidelines

Item	Acceleration, g	
	No Damage Probable	Minor Damage Probable
Pumps (centrifugal) up to 100 hp	4.5	8
Computer air-conditioning units	4.5	N/A
Variable-air-volume (VAV) boxes	3.5	8
Control panel	2	N/A
Fans (centrifugal and axial) up to 100 hp	4	9
Welded steel piping (up to 16 in. diameter), schedule 30 and up	4	8
Rooftop units, curb-mounted	3	6
Air-handling units (AHUs) to 63 ft^2 coil area	4.5	10
Duct		
Rectangular steel	4.5	9
Round steel	4.5	10
MCC motor control centers (MCC)	2.5	N/A
Branch circuit lighting and power panels	3.5	N/A
Uninterruptible power supply (UPS) system	3	N/A
System control cab	3.5	N/A
Battery racks	3.5	7
Substation switch gear	3.5	N/A
Substation transformers	2	N/A
Cable tray to 36 in.	4.5	8
Bus duct	4.5	8
Water heater	3	6
Cooling towers:		
Ceramic	2.5	4
Steel, 1 or 2 cells	4	8
3 cells or more	3.5	6
Wood	4	8
Chillers:		
Centrifugal	4	N/A
Absorption	4.5	N/A
Screw	3.5	N/A
Air-cooled	3.0	N/A
Boilers, fire tube	3.5	N/A
Air compressor, tank mounted		
to 5 hp	4.5	8
7.5 to 20 hp	4	7
Frame mounted, 20 to 100 hp	3.5	7

Sources: ASHRAE (2000), Cover et al. (1985), DOD (1990, 2002), Bulletin No. 32 Shock, Vibration and Associated Environments—Protective Construction Part III, Seismic Fragility based on Test Data—Takanori Ogata July 1992, Seismic Fragility Analysis of Structures and Components for HFBR Facilities BNL-46561, and Chapter 50 of the 1995 *ASHRAE Handbook—HVAC Applications*.

must be capable of analyzing nonlinear supports and site-specific ground motions. This dynamic analysis provides the maximum seismic input accelerations to the equipment components, allowing comparison to three-dimensional shock (drop) or shaker test fragility levels to determine equipment survivability. Actual drop or shaker test data for all HVAC equipment may not be available for the next several years. Table 1 provides minimum fragility level guidelines to help evaluate the equipment's survivability.

Using the response spectra in the code for ground-floor inputs, or the spectra in ATC 29-2 for upper floors, a dynamic analysis can yield maximum input accelerations to equipment components. Comparing them to the allowable acceleration values in the table helps the engineer assess equipment survivability. Dynamic analysis can also provide maximum movement at all connections and, when added to the floor-to-ceiling code-mandated movements, allows the engineer to design these flexible connections and avoid pull-out or shear failures at these locations.

Under some conditions, Chapter 17 of IBC 2000/2003 requires certificates of compliance for components and their attachments for a component importance factor I_p [see Equations (1)] of 1.0 or 1.5.

Table 2 IBC 2000/2003 Seismic Analysis Requirements

Seismic Use Group (Building)	Component Operation Required for Life Safety	Building Seismic Design Category*	Required Analysis Type			
			Anchorage	Equipment Structural Capacity	Equipment Operational Capacity	Certificate of Compliance
I, II, III	No	A	Not required	Not required	Not required	Not required
I, II	No	B, C	Not required	Not required	Not required	Not required
I, II	No	D	Static	Dynamic or test	Not required	For mounting only
I, II	Yes	C, D	Static	Dynamic or test	Dynamic or test	For continued operation
I, II	No	E	Static	Dynamic or test	Dynamic or test	For continued operation
III	No	C, D	Static	Not required	Not required	Not required
III	Yes	C, D	Static	Dynamic or test	Dynamic or test	For continued operation
III	No	F	Static	Dynamic or test	Not required	For mounting only
III	Yes	F	Static	Dynamic or test	Dynamic or test	For continued operation

*If in question, reference structural documents

Table 3 Coefficients for Mechanical Components (2000/2003 IBC and NFPA *Code* 5000)

Mechanical and Electrical Component or Element	a_p	R_p
General Mechanical		
Boilers and furnaces	1.0	2.5
Piping		
High-deformability elements and attachments	1.0	3.5
Limited-deformability elements and attachments	1.0	2.5
Low-deformability elements or attachments	1.0	1.25
HVAC Equipment		
Vibration isolated	2.5	2.5
Non-vibration isolated	1.0	2.5
Mounted in-line with ductwork	1.0	2.5

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This is a life safety issue as well as an essential equipment issue. Essential equipment with an $I_p = 1.5$ must have a certificate of compliance. Issuance of a certificate of compliance to the engineer of record and building official can be based on dynamic analysis. Most building officials require a stamp by a registered professional to be part of the calculations and certificate of compliance. Table 2 provides guidance on type of analysis (static or dynamic) and certificate of compliance documentation is required. Sample dynamic analysis is beyond the scope of this chapter and should be provided by experienced registered professionals. A common approach assumes an elastic response spectrum. The results of the dynamic analysis can then be scaled up or down as a percentage of the total lateral force obtained from the static analysis performed on the building.

Dynamic analysis of piping, ductwork, and equipment reflects the response of the equipment for all earthquake-generated frequencies. Especially for piping and equipment, when the earthquake forcing frequencies match the natural frequencies of the system, the resulting applied forces increase.

Establishing Design Static Force

This chapter details code requirements for the 2000 and 2003 IBC (International Building Code), the 1997 UBC (Uniform Building Code) and the 1994 UBC. The 2000 IBC is expected to become the single national building code for the United States; however, the 1997 UBC and its associated maps are not expected to be replaced internationally for some time.

Until new spectral maps are available for locations outside of the United States, seismic design forces for these areas should be determined based on the older seismic "zone" and ground motion data that are available. Because these data are not compatible with the 2000 IBC design equations, the design force should be determined based on criteria in the 1997 UBC.

To address the bulk of applications, design parameters used by all three versions of the design codes are discussed.

Static Analysis as Defined in the International Building Code

The 2000 and 2003 IBC and NFPA *Code* 5000 specifies a design lateral force F_p for nonstructural components as

$$F_p = (0.4 a_p S_{DS} W_p)\frac{I_p}{R_p}\left(1 + 2\frac{z}{h}\right) \qquad (1)$$

but F_p need not be greater than

$$F_p = 1.6\, S_{DS}\, I_p\, W_p \qquad (2)$$

nor less than

$$F_p = 0.3 S_{DS}\, I_p\, W_p \qquad (3)$$

$$S_{DS} = 2 F_a S_S / 3 \qquad (4)$$

where

a_p = component amplification factor in accordance with Table 3.

S_{DS} = design spectral response acceleration at short periods. S_S is the mapped spectral acceleration from Figure 1 and $0.8 \leq F_a \leq 2.5$. (*Note*: More detailed maps for the United States are available at the U.S. Geological Survey Web site: www.usgs.gov)

F_a = function of site soil characteristics and must be determined in consultation with either project geotechnical (soils) or structural engineer. Values for F_a for different soil types are given in Table 4. (*Note*: Without an approved geotechnical report, the default site soil classification is assumed to be site class *D*.)

R_p = component response modification factor in accordance with Table 4, IBC 2000/2003. (*Note*: If shallow-embedment post-installed anchors, shallow adhesive anchors, or shallow cast-in-place anchors are used, then $R_p = 1.5$. Shallow embedment is defined as $L/d < 8$.)

I_p = component importance factor = 1.5 if one of the following four criteria is met, otherwise 1.0: (1) life safety component required to function after an earthquake, (2) component contains higher than exempted amount of hazardous flammable material, (3) storage rack in occupancies open to general public, and (4) component is needed for continued operation of a Use Group III facility (Table 5).

$1 + 2z/h$ = height amplification factor where z is the height of attachment in the structure and h is the average height of the roof above grade. The value of $z \geq 0$ and z/h need not exceed 1.

W_p = weight of equipment, which includes all items attached or contained in the equipment

If the equipment being analyzed is isolated, the final computed force must be doubled per section 1621.3.1 of the code.

Fig. 1A   Maximum Considered Earthquake Ground Motion for the United States
0.2 s spectral response acceleration (% *g*) (5% of critical damping) Site Class B
(Electronic version also available at the USGS web site http://geohazards.cr.usgs.gov/eq)
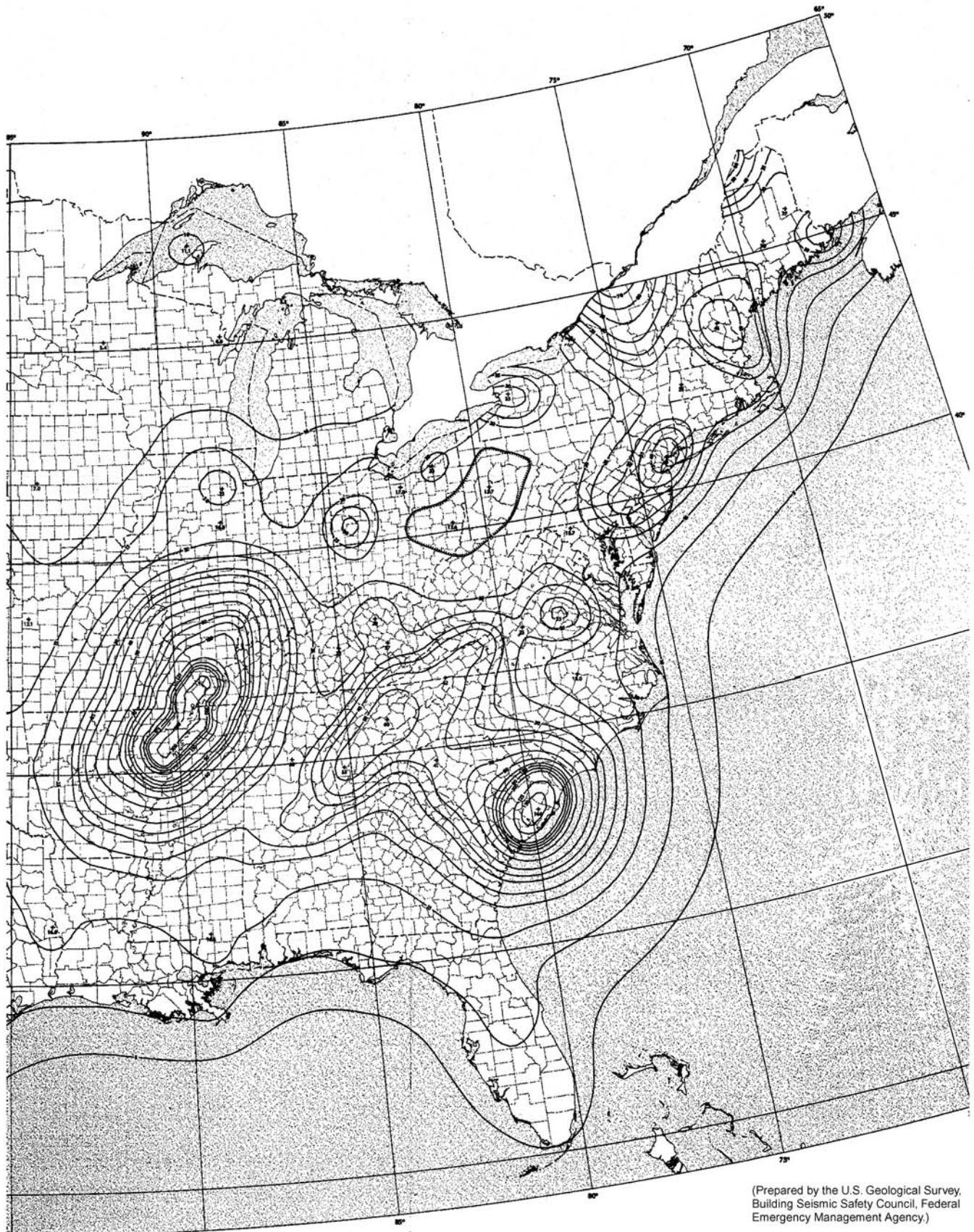
Fig. 1B   Maximum Considered Earthquake Ground Motion for the United States (*Concluded*)

0.2 s spectral response acceleration (% *g*) (5% of critical damping) Site Class B

(Electronic version also available at the USGS web site http://geohazards.cr.usgs.gov/eq)

(Prepared by the U.S. Geological Survey, Building Seismic Safety Council, Federal Emergency Management Agency.)

Per section 1621.1.7 of the code, forces used when computing the loads for shallow (under 8 bolt diameter) embedment anchors are to be increased by a factor of $1.3R_p$.

Per section 1621.3.12.2 of the code, the only permitted expansion anchors for non-vibration-isolated equipment over 10 hp are undercut anchors.

Static Analysis as Defined in 1997 Uniform Building Code

The 1997 UBC specifies a design lateral force F_p for nonstructural components as

$$F_p = \left(a_p C_a \frac{I_p}{R_p} \right) \left(1 + \frac{3h_x}{h_r} \right) W_p \tag{5}$$

but F_p need not be greater than

$$F_p = 4 C_a I_p W_p \tag{6}$$

nor less than

$$F_p = 0.7 C_a I_p W_p \tag{7}$$

where

a_p = component amplification factor in accordance with Table 6

C_a = seismic coefficient (determined from Figure 2 and Tables 7, 8, 9, and 10 as appropriate)

R_p = component response modification factor in accordance with Table 6

I_p = component importance factor in accordance with Table 11

$1 + \dfrac{3h_x}{h_r}$ = height amplification factor where h_x is height of attachment in structure and h_r is average height of roof above grade. The value of $h_x \geq 0$ and h_x/h_r need not exceed 1.

W_p = weight of equipment, including all items attached to or contained in equipment

Static Analysis as Defined in 1994 Uniform Building Code

(*Note*: This version of the Code is obsolete in most jurisdictions. Prior to use, its applicability must be verified by local authorities.)

The total design lateral seismic force is given as

$$F_p = Z I_p C_p W_p \tag{8}$$

where

F_p = total design lateral seismic force

Z = seismic zone factor

I_p = importance factor (set equal to 1.5 for equipment)

C_p = horizontal force factor

W_p = weight of equipment

Figure 2 and Table 10 may be used to determine the seismic zone. The seismic zone factor Z can then be determined from Table 7.

Table 4 Values of Site Coefficient F_a as Function of Site Class and Mapped Spectral Response Acceleration at 1 s Period (S_s)

Site Class	Soil Profile Name	Mapped Spectral Response Acceleration at Short Periods[a]				
		$S_s \leq 0.25$	$S_s = 0.50$	$S_s = 0.75$	$S_s = 1.00$	$S_s \geq 1.25$
A	Hard rock	0.8	0.8	0.8	0.8	0.8
B	Rock	1.0	1.0	1.0	1.0	1.0
C	Very dense soil and soft rock	1.2	1.2	1.1	1.0	1.0
D[c]	**Stiff soil profile**	**1.6**	**1.4**	**1.2**	**1.1**	**1.0**
E	Soft soil profile	2.5	1.7	1.2	0.9	b
F		See 2000 IBC Table 1615.1.1 and Note b				

[a]Use straight-line interpolation for intermediate values of mapped spectral acceleration at short period S_s.
[b]Site-specific geotechnical investigation and dynamic site response analyses must be performed to determine appropriate values.
[c]D is the default Site Class unless otherwise stated in the approved geotechnical report.

Table 5 Seismic Groups and Building Importance Factors (2000 IBC)

Seismic Group	Building Importance Factor	Nature of Occupancy
I	1.0	Buildings and other structures except those listed in Groups II, III, IV
II	1.25	1. Structures where more than 300 people congregate in one area 2. Structures with elementary, secondary school or day care facilities with capacity of over 250 3. Structures with capacity greater than 500 for colleges or adult education facilities 4. Health care facilities with capacity of 50 or more resident patients but no surgery or emergency treatment facilities 5. Jails and detention facilities 6. Any other occupancy with occupant load greater than 5000 7. Power-generating stations, water treatment for potable water, wastewater treatment facilities and other public utility facilities not included in Group III 8. Buildings and other structures not included in Group III containing sufficient quantities of toxic or explosive substances to be dangerous to the public if released
III	1.5	1. Hospitals and other health care facilities with surgery or emergency treatment facilities 2. Fire, rescue, and police stations and emergency vehicle garages 3. Designated earthquake, hurricane, or other emergency shelters 4. Designated emergency preparedness, communication and operation centers and other facilities required for emergency response 5. Power-generating stations and other public utility facilities required as emergency back-up facilities for Group III structures 6. Structures containing highly toxic materials as defined by Section 307 where quantity of material exceeds the exempt amounts of Table 307.7(2) 7. Aviation control towers, air traffic control centers and emergency aircraft hangers 8. Structures with critical national defense functions 9. Water treatment facilities required to maintain water pressure for fire suppression
IV	1	Structures that represent a low threat to human life in the event of failure including, but not limited to agricultural facilities, certain temporary facilities, and minor storage facilities

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Table 6 Coefficients for Mechanical Components (1997 UBC)

Mechanical and Electrical Component or Element	a_p	R_p
Equipment		
Tanks and vessels	1.0	3.0
Electrical, mechanical, plumbing equipment and piping, ducts and conduit	1.0	3.0
Equipment braced or anchored below center of mass	2.5	3.0
Emergency power, communication equipment and batteries/fuel for equipment use		
Other		
Rigid components with ductile material and attachments	1.0	3.0
Rigid components with nonductile material and attachments	1.0	1.5
Flexible components with ductile material and attachments	2.5	3.0
Flexible components with nonductile material and attachments	2.5	1.5
Vibration isolated		
Nonshallow or expansion anchor attachment	2.5	1.5
Shallow or expansion anchor attachment	2.5	0.75

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Table 7   Seismic Zone Factor *Z* (1994 and 1997 UBC)

Zone	*Z*
1	0.075
2A	0.15
2B	0.20
3	0.30
4	0.40

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Seismic Design for Buildings (Army, Navy, and Air Force 1992) can also be used to determine the seismic zone.

The importance factor I_p from the UBC (ICBO 1994) ranges from 1 to 1.5, depending on the building occupancy and hazard level. For equipment, I_p should be conservatively set at 1.5.

The horizontal force factor C_p is determined from Table 12 based on type of equipment, the tie-down configuration, and type of base.

The weight W_p of equipment should include all items attached or contained in the equipment.

APPLYING STATIC ANALYSIS

The forces acting on a piece of equipment are vertical and lateral forces resulting from the earthquake, the force of gravity, and forces at the restraints that hold the equipment in place. The analysis assumes that the equipment does not move during the earthquake and that the relative accelerations between its center of gravity and the ground generate forces that must be balanced by reactions at the restraints. Guidance from the code bodies indicates that equipment can be analyzed as though it were a rigid component; however, a factor a_p is applied within the computation to address flexibility issues on particular equipment types or flexible mounting arrangements. (*Note*: for dynamic analysis, it is common to use a 5% damping factor for equipment and a 1% damping factor for piping.) Although the basic force computation is different, the details of load distribution in the examples that follow apply independently of the code used.

Table 8   Seismic Coefficient C_a (1997 UBC)

Soil Profile Type	Seismic Zone Factor, Z				
	1	2A	2B	3	4
S_A	0.06	0.12	0.16	0.24	$0.32N_a$
S_B	0.08	0.15	0.20	0.30	$0.40N_a$
S_C	0.09	0.18	0.24	0.33	$0.40N_a$
S_D	0.12	0.22	0.28	0.36	$0.44N_a$
S_E	0.19	0.30	0.34	0.36	$0.36N_a$
S_F	Requires site-specific dynamic response analysis				

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General soil profile descriptions are as follows [see UBC (1997) for more detailed information]:
S_A = Hard rock >5000 ft/s shear wave velocity
S_B = Rock with shear wave velocity > 2500 ft/s but < 5000 ft/s
S_C = Dense soil/soft rock with shear wave velocity > 1200 ft/s but < 2500 ft/s
S_D = Stiff soil with shear wave velocity > 600 ft/s but < 1200 ft/s
S_E = Soil with shear wave velocity < 600 ft/s
S_F = Soils requiring site-specific evaluation

Table 9   Near Source Factor N_a (1997 UBC)

Seismic Source Type	Closest Distance to Known Seismic Source		
	≤1.25 miles	3.1 miles	≥6.2 miles
A	1.5	1.2	1.0
B	1.3	1.0	1.0
C	1.0	1.0	1.0

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Notes: 1. Interpolation between tabulated values is permitted.
  2. Source type must be as determined by approved geological data.

The forces acting on the restraints include both shear and tensile components. The application direction of the lateral seismic acceleration can vary and is unknown. Depending on its direction, it is likely that not all of the restraints will be affected or share the load equally. It is important to determine the worst-case combination of forces at all restraint points for any possible direction that the lateral wave front can follow to ensure that the attachment is adequate.

Once the overall seismic forces F_p and F_{pv} have been determined (as indicated in the previous section or per the local code requirement), the loads at the restraint points can be determined. There are many different valid methods that can be used to determine these loads, but this section suggests a couple of simple approaches.

Under some instances (particularly those relating to life support issues in hospital settings), newer code requirements indicate that critical equipment must be seismically qualified to ensure its continued operation during and after a seismic event. Special care must be taken in these situations to ensure that equipment has been shaker tested or otherwise certified to meet the maximum anticipated seismic load.

COMPUTATION OF LOADS

The forces acting on the equipment are the lateral and vertical forces resulting from the earthquake, the force of gravity, and the forces of the restraint holding the equipment in place. The analysis assumes the equipment does not move during an earthquake; thus, the sum of the forces and moments must be zero. When calculating the overturning moment, including an uplift factor, the vertical component F_{pv} at the center of gravity is typically defined to be
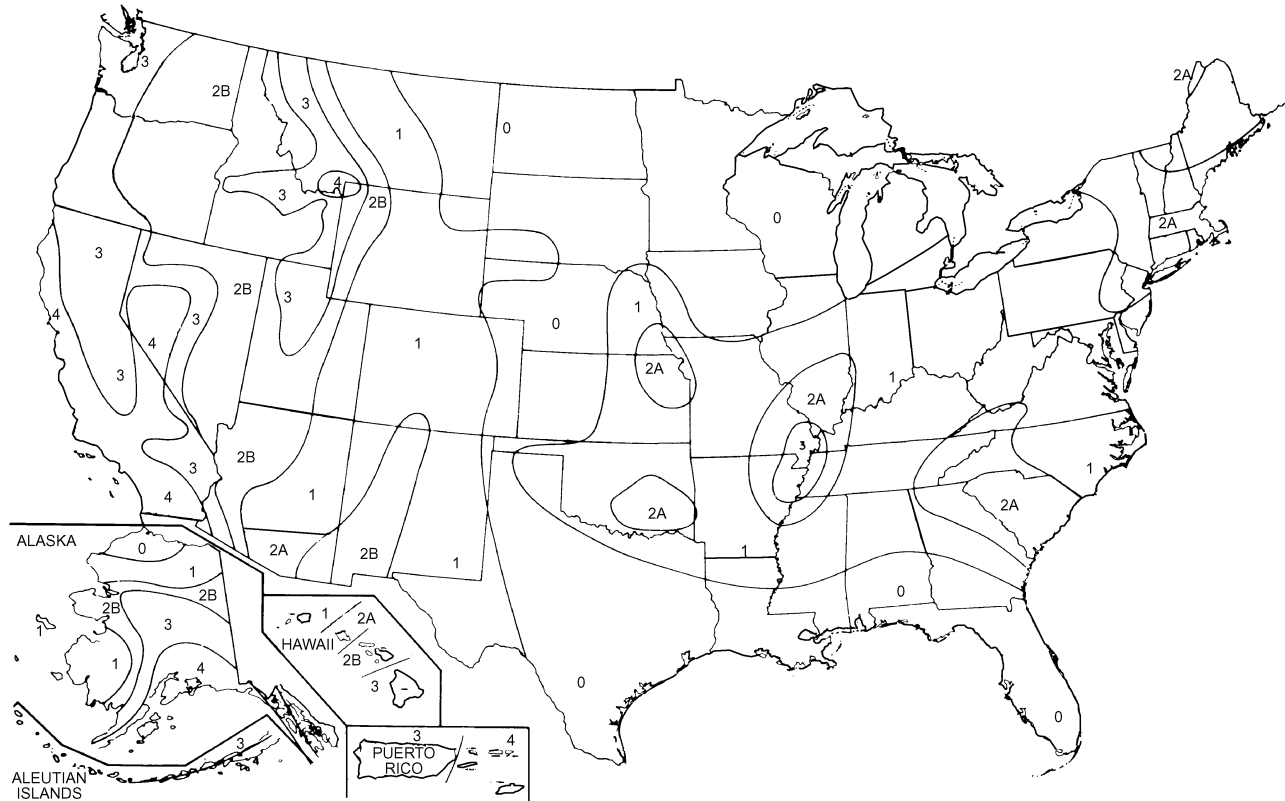
Fig. 2   Seismic Zone Map of the United States (1994 and 1997 UBC)

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$$F_{pv} = F_p/3 \text{ (for older codes)} \tag{9a}$$

$$F_{pv} = 0.5C_a I_p W_p \text{ (for the 1997 UBC if specified)} \tag{9b}$$

$$F_{pv} = 0.2S_{DS}D \text{ (for the 2000 IBC)} \tag{9c}$$

when using allowable strength-based design factors, where

D = dead load affect
S_{DS} = short-period spectral response (0.2 s)

The forces of the restraint holding the equipment in position include shear and tensile forces. It is important to determine the number of bolts that are affected by the earthquake forces. The direction of the lateral force should be evaluated in both horizontal directions, as shown in Figure 3. All bolts or as few as a single bolt may be affected.

Simple Case

Figure 3 shows a rigid floor-mount installation of a piece of equipment with the center of gravity at the approximate center of the restraint pattern. To calculate the shear force, the sum of the forces in the horizontal plane is

$$0 = F_p - V \tag{10}$$

The effective shear force per restraint V_{eff} is

$$V_{eff} = F_p/N_{bolt} \tag{11}$$

where N_{bolt} is the number of bolts in shear.

The equipment shown in Figure 3 has two bolts on each side, so that four bolts are in shear. Using a single-axis moment equation to calculate the tension force, the sum of the moments for overturning are as follows:

$$F_p h_{cg} - (W_p - F_p/3)(D_1/2) - TD_1 = 0$$
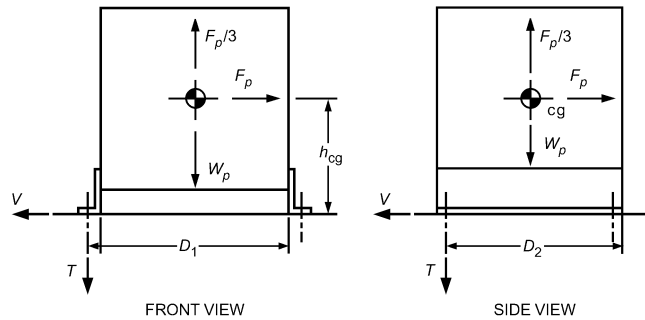
Fig. 3   Equipment with Rigidly Mounted Structural Bases

Thus,

$$T = [F_p h_{cg} - (W_p - F_p/3)(D/2)]/D \quad \text{(where } D = D_1 \text{ or } D_2) \tag{12}$$

For the example shown in Figure 3, two bolts are in tension. The effective tension force T_{eff}, where overturning affects only one side, is

$$T_{eff} = T/N_{bolt} \tag{13}$$

Shear and tension forces V and T should be calculated independently for both axes, as shown in the front and side views. The results must be combined using the larger result + 0.3 times the smaller result to account for out-of-axis forces.

Equations (9), (10), and (11) may be applied to ceiling-mounted equipment. Equation (12) must be modified to Equation (14) because the mass of the equipment adds to the overturning moment. Summing the moments determines the effective tension force on one axis as

Table 10 International Seismic Zones (1994 and 1997 UBC)

Country	City	Seismic Zone	Country	City	Seismic Zone	Country	City	Seismic Zone
Albania	Tirana	3	Germany (*Continued*)	Dusseldorf	1	Norway	Oslo	2B
Algeria	Algiers	4		Frankfurt	1	Oman	Muscat	2B
	Oran	4		Hamburg	0	Pakistan	Islamabad	4
Angola	Luanda	0		Munich	1		Karachi	2B
Antigua and Barbuda	St. Johns	3		Stuttgart	2B		Lahore	2B
Argentina	Buenos Aires	0	Ghana	Accra	3		Peshawar	3
Armenia	Yerevan	3	Greece	Athens	3	Panama	Panama City	2B
Australia	Brisbane	1		Thessaloniki	4	Papua New Guinea	Port Moresby	3
	Canberra	1	Grenada	St. George's	3	Paraguay	Asuncion	0
	Melbourne	1	Guatemala	Guatemala City	4	Peru	Lima	4
	Perth	1	Guinea	Conakry	0	Philippines	Baguio	3
	Sydney	1	Guinea-Bissau	Bissau	0		Cebu	4
Austria	Salzburg	2B	Guyana	Georgetown	0		Manila	4
	Vienna	2B	Haiti	Port-au-Prince	3	Poland	Krakow	2B
Azerbaijan	Baku	3	Honduras	Tegucigalpa	3		Poznan	1
Bahamas	Nassau	0	Hong Kong	Hong Kong	2B		Warsaw	1
Bahrain	Manama	0	Hungary	Budapest	2B	Portugal	Azor	3
Bangladesh	Dhaka	3	Iceland	Reykjavik	4		Lisbon	3
Barbados	Bridgetown	3	India	Bombay	3		Oporto	2B
Belarus	Minsk	1		Calcutta	2B		Ponta Delgada	3
Belgium	Antwerp	1		Madras	1	Qatar	Doha	0
	Brussels	1		New Delhi	2B	Romania	Bucharest	3
Belize	Belize City	1	Indonesia	Jakarta	3	Russia	Khabarovsk	1
Benin	Cotonou	0		Medan	3		Moscow	1
Bermuda	Hamilton	0		Surabaya	3		St. Petersburg	0
Bolivia	La Paz	3	Iraq	Baghdad	2B		Vladivostok	1
Botswana	Gaborone	0	Ireland	Dublin	0	Rwanda	Kigali	3
Brazil	Belo Horizonte	0	Israel	Jerusalem	3	Saudi Arabia	Dhahran	0
	Brasilia	0		Tel Aviv	1		Jeddah	2B
	Porto Alegre	0	Italy	Florence	3		Riyadh	0
	Recife	0		Genoa	2B	Senegal Republic	Dakar	0
	Rio de Janeiro	0		Milan	2B	Seychelles Islands	Victoria	0
	São Paulo	1		Naples	2B	Sierra Leone	Freetown	0
Brunei	Bandar Seri Begawan	1		Palermo	4	Singapore	Singapore	1
Bulgaria	Sofia	3		Rome	2B	Slovakia	Bratislava	2B
Burkina Faso	Ouagadougou	0	Ivory Coast	Abidjan	3	Somalia	Mogadishu	0
Burma	Mandalay	3	Jamaica	Kingston	3	South Africa	Cape Town	2B
	Rangoon	2B	Japan	Fukuoka	3		Durban	2B
Burundi	Bujumbura	3		Kobe	3		Johannesburg	2B
Cameroon	Douala	0		Naha	3		Pretoria	2B
	Yaounde	0		Okinawa	3	Spain	Barcelona	2B
Canada	Calgary	1		Osaka	3		Bilbao	2B
	Halifax	1		Sapporo	3		Madrid	0
	Montreal	2A		Tokyo	4	Sri Lanka	Colombo	0
	Ottawa	2A	Jordan	Amman	3	Sudan	Khartoum	2B
	Quebec	3	Kazakhstan	Alma-Ata	4	Suriname	Paramaribo	0
	Toronto	1	Kenya	Nairobi	2B	Swaziland	Mbabane	2B
	Vancouver	3	Korea	Seoul	2A	Sweden	Stockholm	0
Cape Verde	Praia	0	Kuwait	Kuwait	1	Switzerland	Bern	2B
Central African Republic	Bangui	0	Kyrgyzstan	Bishkek	4		Geneva	1
Chad Republic	N'Djamena	0	Laos	Vientiane	1		Zurich	2B
Chile	Santiago	4	Latvia	Riga	1	Syrian Arab Republic	Damascus	3
China	Beijing (Peking)	3	Lebanon	Beirut	3	Taiwan	Taipei	4
	Chengdu	3	Lesotho	Maseru	2B	Tajikistan	Dushanbe	4
	Guangzhou (Canton)	2B	Liberia	Monrovia	1	Tanzania	Dar Es Salaam	2B
	Shanghai	2B	Lithuania	Vilnius	1		Zanzibar	2B
	Shenyang (Mukden)	4	Luxembourg	Luxembourg	1	Thailand	Bangkok	1
Colombia	Barranquilla	2B	Madagascar	Antananarivo	0		Chiang Mai	2B
	Bogota	3	Malawi	Lilongwe	3		Songkhla	0
Congo	Brazzaville	0	Malaysia	Kuala Lumpur	1	Togo	Lome	1
Costa Rica	San Jose	3	Mali Republic	Bamako	0	Trinidad and Tobago	Port of Spain	3
Cuba	Havana	1	Malta	Valletta	2B	Tunisia	Tunis	3
Cyprus	Nicosia	3	Martinique	Martinique	3	Turkey	Adana	2B
Czech Republic	Prague	1	Mauritania	Nouakchott	0		Ankara	2B
Denmark	Copenhagen	1	Mauritius	Port Louis	0		Istanbul	4
Djibouti	Djibouti	3	Mexico	Cuidad Juarez	2B		Izmir	4
Dominican Republic	Santo Domingo	3		Guadalajara	3	Turkmenistan	Ashkhabad	4
Ecuador	Guayaquil	3		Hermosillo	3	Uganda	Kampala	2B
	Quito	4		Matamoros	0	Ukraine	Kiev	1
Egypt	Alexandria	2B		Merida	0	United Arab Emirates	Abu Dhabi	0
	Cairo	2B		Mexico City	3		Dubai	0
El Salvador	San Salvador	4		Monterrey	0	United Kingdom	Belfast	0
Equatorial Guinea	Malabo	0		Nuevo Laredo	0		Edinburgh	1
Estonia	Tallinn	2A		Tijuana	3		London	1
Ethiopia	Addis Ababa	3	Moldova	Kishinev	2B	Uruguay	Montevideo	0
	Asmara	3	Morocco	Casablanca	2B	Uzbekistan	Tashkent	3
Fiji Islands	Suva	3		Rabat	2B	Vatican City	Vatican City	2B
Finland	Helsinki	1	Mozambique	Maputo	2B	Venezuela	Caracas	3
France	Bordeaux	2B	Nepal	Kathmandu	3		Maracaibo	2B
	Lyon	1	Netherlands	Amsterdam	0	Vietnam	Ho Chi Minh City	0
	Marseille	2B		The Hague	0	Yemen Arab Republic	Aden City	3
	Paris	0	Netherlands Antilles	Curacao	3		Sana	3
	Strasbourg	2B	New Zealand	Auckland	2B	Yugoslavia	Belgrade	2A
Gabon	Libreville	0		Wellington	4		Zagreb	3
Gambia	Banjul	0	Nicaragua	Managua	4	Zaire	Kinshasa	0
Georgia	Tbilisi	3	Niger Republic	Niamey	0		Lubumbashi	2B
Germany	Berlin	0	Nigeria	Kaduna	0	Zambia	Lusaka	2B
	Bonn	1		Lagos	0	Zimbabwe	Harare	2B

Table 11   Occupancy Category and Importance Factor (1997 UBC)

Occupancy Category	Importance Factor	Nature of Occupancy
1	1.5	Essential facilities 1. Hospitals and other health care facilities with surgery or emergency treatment facilities 2. Fire, rescue, and police stations and emergency vehicle garages 3. Structures and shelters for emergency preparedness centers 4. Structures and equipment in government communication centers and other facilities required for emergency response 5. Standby power-generating equipment for Category 1 facilities 6. Aviation control towers and emergency aircraft hangers 7. Tanks or other structures containing housing or supporting water or other fire suppression material or equipment required for the protection of Category 1, 2, or 3 structures
2	1.5	Hazardous facilities 1. Group H, Division 1, 2, 6, and 7 occupancies and structures housing or supporting toxic or explosive chemicals or substances 2. Nonbuilding structures housing, supporting, or containing quantities of toxic or explosive substances that, if contained within a building, would cause that building to be classified as a Group H, Division 1, 2, or 7 occupancy
3	1.0	Special occupancy structures 1. Group A, Division 1, 2, and 2.1 occupancies 2. Buildings housing Group E, Division 1 and 3 occupancies with capacity of greater than 300 students 3. Buildings housing Group B occupancies used for college or adult education with capacity of greater than 500 students 4. Group 1, Division 1 and 2 occupancies with 50 or more resident incapacitated patients, but not included in Category 1 5. Group 1, Division 3 occupancies 6. All structures with occupancy greater than 5000 persons 7. Structures and equipment in power-generating stations and other public utility facilities not included in Category 1 or Category 2 above, and required for continued operation
4	1.0	Standard occupancy structures All structures housing occupancies or with functions not listed in Category 1, 2, or 3, and Group U occupancy towers
5	1.0	Miscellaneous structures Group U occupancy except for towers

Source: Uniform Building Code (1997). Reproduced from the 1997 edition of the *Uniform Building Code*™, Copyright © 1997, with permission of the publisher, the International Conference of Building Officials. ICBO assumes no responsibility for the accuracy or the completeness of summaries provided herein.

Table 12   Horizontal Force Factor C_p (1994 UBC)

Equipment or nonstructural components	1
Mechanical equipment, plumbing, and electrical equipment and associated piping rigidly mounted	0.75
All equipment resiliently mounted (maximum 2.0)	2

Source: Uniform Building Code (1994). Reproduced from the 1994 edition of the *Uniform Building Code*™, Copyright © 1994, with permission of the publisher, the International Conference of Building Officials. ICBO assumes no responsibility for the accuracy or the completeness of summaries provided herein.
Note: Stacks and tanks should be evaluated for compliance with applicable codes by a qualified engineer.

IBC 2000/2003 does not use seismic zones. Table 13 is a brief listing of S_s factors that can be used in IBC 2000 and 2003 to calculate the magnitude of the horizontal static seismic force acting at the equipment center of gravity. Values for IBC 2006 are available on the USGS Web site.

$$T = [F_p h_{cg} + (W_p + F_p/3)(D_1/2)]/D_1 \qquad (14)$$

Interaction Formula. To evaluate the combined effective tension and shear forces that act simultaneously on the bolt, use the following equation:

$$(T_{eff}/T_{allow})^{5/3} + (V_{eff}/V_{allow})^{5/3} \le 1.0 \qquad (15)$$

Allowable forces T_{allow} and V_{allow} are generic capacities given in Table 14 for wedge anchor bolts.

General Case

The classic method used to distribute seismic loads equally distributes lateral loads among the restraints and then modifies these loads as a function of the weight eccentricity. Worst-case weight, vertical seismic load, and overturning components are combined to determine a maximum vertical load component. Although simple to perform, this method tends to concentrate the seismic load resisting forces into the corners and can (particularly in seismically active areas) generate a solution that is difficult, in practice, to implement. This **polar method** is in common use and works well for most applications.

A second, somewhat more complex technique, the **lump mass method**, proportions the restraint loads based on the equipment weight and distribution. When working with larger seismic forces or unstable equipment, this offers the option of more evenly distributing the seismic load, reducing anchor size and peak restraint requirements. Because eccentric center of gravity (cg) loads are not required to be carried out to the corner restraints as in the polar method, this technique deemphasizes stresses in the equipment frame and is more suitable for nonrigid equipment types.

Note: *Although only two methods of computing forces for more general equipment cases are illustrated here, there are many other valid methods that can be used to distribute the restraint forces. It is important that any method used include the ability to account for equipment weight, seismic uplift forces, overturning forces, and an offset center of gravity within the equipment.*

Polar Method

Determination of Lateral Seismic Forces at Restraints. Lateral forces are equally distributed among the restraints. If the equipment's center of gravity does not coincide with its geometric center, a rotational factor is added to account for the imbalance. This factor is determined in three steps. First, compute the true chord length in the horizontal plane between the equipment's center of gravity and the restraints' geometric center. Second, multiply the equipment total seismic lateral force by this length (to obtain a rotational moment). Third, divide this figure by the number of moment-resisting restraints times their distance from the geometric center. (The moment-resisting restraints are those farthest and equally spaced from the geometric center.) The resulting load can then be added to

Table 13A S_s Numbers* for Selected U.S. Locations (U.S. COE 1998)

State, City	ZIP	S_s	State, City	ZIP	S_s	State, City	ZIP	S_s	State, City	ZIP	S_s
Alabama			Ft. Wayne	46835	0.162	Butte	59701	0.599	**Rhode Island**		
Birmingham	35217	0.328	Gary	46402	0.173	Great Falls	59404	0.248	Providence	02907	0.267
Mobile	36610	0.124	Indianapolis	46260	0.182	**Nebraska**			**South Carolina**		
Montgomery	36104	0.170	South Bend	46637	0.121	Lincoln	68502	0.177	Charleston	29406	1.56
Arkansas			**Kansas**			Omaha	68144	0.127	Columbia	29203	0.578
Little Rock	72205	0.461	Kansas City	66103	0.122	**Nevada**			**South Dakota**		
Arizona			Topeka	66614	0.184	Las Vegas	89106	0.637	Rapid City	57703	0.153
Phoenix	85034	0.226	Wichita	67217	0.142	Reno	89509	1.29	Sioux Falls	57104	0.113
Tuscon	85739	0.325	**Kentucky**			**New York**			**Tennessee**		
California			Ashland	41101	0.221	Albany	12205	0.275	Chattanooga	37415	0.500
Fresno	93706	0.592	Covington	41011	0.186	Binghampton	13903	0.185	Knoxville	37920	0.589
Los Angeles	90026	1.50	Louisville	40202	0.247	Buffalo	14222	0.319	Memphis	38109	1.25
Oakland	94621	1.55	**Louisiana**			Elmira	14905	0.173	Nashville	37211	0.305
Sacramento	95823	0.568	Baton Rouge	70807	0.144	New York	10014	0.425	**Texas**		
San Diego	92101	1.54	New Orleans	70116	0.130	Niagara Falls	14303	0.311	Amarillo	79111	0.166
San Francisco	94114	1.50	Shreveport	71106	0.165	Rochester	14619	0.248	Austin	78703	0.088
San Jose	95139	2.05	**Massachusetts**			Schenectady	12304	0.278	Beaumont	77705	0.116
Colorado			Boston	02127	0.325	Syracuse	13219	0.192	Corpus Christi	78418	0.093
Colorado Springs	80913	0.178	Lawrence	01843	0.376	Utica	13501	0.250	Dallas	75233	0.117
Denver	80239	0.187	Lowell	01851	0.355	**North Carolina**			El Paso	79932	0.358
Connecticut			New Bedford	02740	0.261	Charlotte	28216	0.345	Ft. Worth	76119	0.110
Bridgeport	06606	0.332	Springfield	01107	0.260	Greensboro	27410	0.255	Houston	77044	0.107
Hartford	06120	0.274	Worcester	01602	0.271	Raleigh	27610	0.211	Lubbock	79424	0.099
New Haven	06511	0.285	**Maryland**			Winston-Salem	27106	0.281	San Antonio	78235	0.133
Waterbury	06702	0.287	Baltimore	21218	0.199	**North Dakota**			Waco	76704	0.095
Florida			**Maine**			Fargo	58103	0.073	**Utah**		
Ft. Lauderdale	33328	0.070	Augusta	04330	0.318	Grand Forks	58201	0.054	Salt Lake City	84111	1.79
Jacksonville	32222	0.142	Portland	04101	0.369	**Ohio**			**Virginia**		
Miami	33133	0.061	**Michigan**			Akron	44312	0.179	Norfolk	23504	0.132
St. Petersburg	33709	0.078	Detroit	48207	0.123	Canton	44702	0.316	Richmond	23233	0.300
Tampa	33635	0.083	Flint	48506	0.091	Cincinnati	45245	0.191	Roanoke	24017	0.290
Georgia			Grand Rapids	49503	0.087	Cleveland	44130	0.197	**Vermont**		
Atlanta	30314	0.258	Kalamazoo	49001	0.116	Columbus	43217	0.164	Burlington	05401	0.446
Augusta	30904	0.419	Lansing	48910	0.109	Dayton	45440	0.206	**Washington**		
Columbia	31907	0.169	**Minnesota**			Springfield	45502	0.216	Seattle	98108	1.51
Savannah	31404	0.402	Duluth	55803	0.056	Toledo	43608	0.171	Spokane	99201	0.315
Iowa			Minneapolis	55422	0.057	Youngstown	44515	0.163	Tacoma	98402	1.23
Council Bluffs	41011	0.186	Rochester	55901	0.055	**Oklahoma**			**Washington, D.C.**		
Davenport	52803	0.130	St. Paul	55111	0.056	Oklahoma City	73145	0.339	Washington	20002	0.178
Des Moines	50310	0.073	**Missouri**			Tulsa	74120	0.160	**Wisconsin**		
Idaho			Carthage	64836	0.149	**Oregon**			Green Bay	54302	0.066
Boise	83705	0.344	Columbia	65202	0.178	Portland	97222	1.04	Kenosha	53140	0.133
Pocatello	83201	0.553	Jefferson City	65109	0.207	Salem	97301	0.929	Madison	53714	0.114
Illinois			Joplin	64801	0.138	**Pennsylvania**			Milwaukee	53221	0.120
Chicago	60620	0.190	Kansas City	64108	0.122	Allentown	18104	0.289	Racine	53402	0.124
Moline	61265	0.135	Springfield	65801	0.120	Bethlehem	18015	0.304	Superior	54880	0.055
Peoria	61605	0.174	St. Joseph	64501	0.120	Erie	16511	0.164	**West Virginia**		
Rock Island	61201	0.131	St. Louis	63166	0.586	Harrisburg	17111	0.224	Charleston	25303	0.206
Rockford	61108	0.170	**Mississippi**			Philadelphia	19125	0.326	Huntington	25704	0.221
Springfield	62703	0.263	Jackson	39211	0.191	Pittsburgh	15235	0.129	**Wyoming**		
Indiana			**Montana**			Reading	19610	0.293	Casper	82601	0.341
Evansville	47712	0.754	Billings	59101	0.134	Scranton	18504	0.232	Cheyenne	82001	0.183

*Nominal values based on ZIP codes. See www.usgs.gov for calculator to check actual S_s using latitude and longitude for best results.

Table 14 Typical Allowable Loads for Wedge Anchors
(obsolete January 2007)

Diameter, in.	T_{allow}, lb	V_{allow}, lb
0.5	600	1200
0.625	900	2200
0.75	1350	3000

Notes:
1. The allowable tensile forces are for installations without special inspection (torque test) and may be doubled if the installation is inspected.
2. Additional tension and shear values may be obtained from published ICC Evaluation Service Reports.

the original (balanced) figure. This method transfers all imbalance loads to the corner restraints and provides a valid method of restraint as long as the equipment acts as a rigid body. The assumption that a piece of equipment can transfer these loads out to the corners becomes less accurate as the equipment becomes less rigid.

Figure 3 shows a typical rigid floor-mounted installation of a piece of equipment with a center of gravity coincident with the geometric center. The maximum weight on a restraint can easily be calculated using

$$W_n = -W_p/N_{bolt} + T_e \tag{16}$$

where T_e is a weight eccentricity factor computed as noted in the previous paragraph and the effective shear force V_{eff} is

$$V_{eff} = F_p/W_p(W_n) \tag{17}$$

(*Note*: For an example of a case with the center of gravity offset, see Example 3.)

Determination of Vertical Seismic Forces at Restraints. Calculation of the tensile/compressive forces at the restraints is more complex than that for determining the shear loads, and must include weight, vertical seismic force, overturning forces, and (if isolated) the type of isolator/restraint system used. The total tensile and compressive forces are the worst-case summation of each of these components. For clarity, each component is addressed here as a separate entity.

Table 13B S_s Numbers for Selected International Locations (U.S. COE 1998)

Country	City	S_s
Africa		
Algeria	Alger	1.24
	Oran	1.24
Angola	Luanda	0.06
Benin	Colonou	0.06
Botswana	Gaborone	0.06
Burkina Faso	Ougadougou	0.06
Burundi	Bujumbura	1.24
Cameroon	Douala	0.06
	Yaounde	0.06
Cape Verde	Praia	0.06
Central African Republic		
	Bangui	0.06
Chad	Ndjamena	0.06
Congo	Brazaville	0.06
Djibouti	Djibouti	1.24
Egypt	Alexandria	0.62
	Cairo	0.62
	Port Said	0.62
Equatorial Guinea		
	Malabo	0.06
Ethiopia	Addis Ababa	1.24
	Asmara	1.24
Gabon	Libreville	0.06
Gambia	Banjul	0.06
Ghana	Accra	1.24
Guinea	Bissau	0.31
	Conakry	0.06
Ivory Coast	Abidjan	0.06
Kenya	Nairobi	0.62
Lesotho	Maseru	0.62
Liberia	Monrovia	0.31
Libya	Tripoli	0.62
	Wheelus AFB	0.62
Madagascar	Tananarive	0.06
Malawi	Blantyre	1.24
	Lilongwe	1.24
	Zomba	1.24
Mali	Bamako	0.06
Mauritania	Nouakchott	0.06
Mauritius	Port Louis	0.06
Morocco	Casablanca	0.62
	Port Lyautey	0.31
	Rabat	0.62
	Tangier	1.24
Mozambique	Maputo	0.62
Niger	Niamey	0.06
Nigeria	Ibadan	0.06
	Kaduna	0.06
	Lagos	0.06
Rwanda	Kigali	1.24
Senegal	Dakar	0.06
Seychelles	Victoria	0.06
Sierra Leone	Freetown	0.06
Somalia	Mogadishu	0.06
South Africa	Cape Town	1.24
	Durban	0.62
	Johannesburg	0.62
	Natal	0.31
	Pretoria	0.62
Swaziland	Mbabane	0.62
Tanzania	Dar es Salaam	0.62
	Zanzibar	0.62
Togo	Lome	0.31
Tunisia	Tunis	1.24
Uganda	Kampaia	0.62
Zaire	Bukavu	1.24
	Kinshasa	0.06
	Lubumbashi	0.62
Zambia	Lusaka	0.62
Zimbabwe	Harare (Sallsbury)	1.24
Asia		
Afghanistan	Kabul	1.65
Bahrain	Manama	0.06
Bangladesh	Dacca	1.24
Brunei	Bandar Seri	
	Begawan	0.31
China	Canton	0.62
	Chengdu	1.24
	Hong Kong	0.62
	Nanking	0.62
	Peking	1.65
	Shanghai	0.62
	Shengyang	1.65
	Tibwa	1.65
	Tsingtao	1.24
	Wuhan	0.62
Cyprus	Nicosia	1.24
India	Bombay	1.24
	Calcutta	0.62
	Madras	0.31
	New Delhi	1.24
Indonesia	Bandung	1.65
	Jakarta	1.65
	Medan	1.24
	Surabaya	1.65
Iran	Isfahan	1.24
	Shiraz	1.24
	Tabriz	1.65
	Tehran	1.65
Iraq	Baghdad	1.24
	Basra	0.31
Israel	Haifa	1.24
	Jerusalem	1.24
	Tel Aviv	1.24
Japan	Fukuoka	1.24
	Itazuke AFB	1.24
	Misawa AFB	1.24
	Naha, Okinawa	1.65
	Osaka/Kobe	1.65
	Sapporo	1.24
	Tokyo	1.65
	Wakkanai	1.24
	Yokohama	1.65
	Yokota	1.65
Jordan	Amman	1.24
Korea	Kwangju	0.31
	Kimhae	0.31
	Pusan	0.31
	Seoul	0.06
Kuwait	Kuwait	0.31
Laos	Vientiane	0.31
Lebanon	Beirut	1.24
Malaysia	Kuala Lumpur	0.31
Myanmar	Mandalay	1.24
	Rangoon	1.24
Nepal	Kathmandu	1.65
Oman	Muscat	0.62
Pakistan	Islamabad	1.68
	Karachi	1.65
	Lahore	0.62
	Peshawar	1.65
Qatar	Doha	0.06
Saudi Arabia	Al Badi	0.31
	Dhahran	0.31
	Jiddah	0.31
	Khamis Mushayt	0.31
	Riyadh	0.06
Singapore	All	0.31
South Yemen	Aden City	1.24
Sri Lanka	Colombo	0.06
Syria	Aleppo	1.24
	Damascus	1.24
Taiwan	All	1.65
Thailand	Bangkok	0.31
	Chinmg Mai	0.62
	Songkhia	0.06
	Udom	0.31
Turkey	Adana	0.62
	Ankara	0.62
	Istanbul	1.65
	Izmir	1.65
	Karamursel	1.24
United Arab Emirates		
	Abu Dhabi	0.06
	Dubai	0.06
Viet Nam		
	Ho Chi Minh City (Saigon)	0.06
Yemen	Sanaa	1.24
Atlantic Ocean Area		
Azorea	All	0.62
Bermuda	All	0.31
Caribbean Sea		
Bahama Islands	All	0.31
Cuba	All	0.62
Dominican Republic		
	Santo Domingo	1.24
French West Indies		
	Martinique	1.24
Grenada	Saint Georges	1.24
Haiti	Port au Prince	1.24
Jamaica	Kingston	1.24
Leeward Islands	All	1.24
Puerto Rico	All	0.83
Trinidad & Tobago		
	All	1.24
Central America		
Belize	Belmopan	0.62
Canal Zone	All	0.62
Costa Rica	San Jose	1.24
El Salvador	San Salvador	1.65
Guatemala	Guatemala	1.65
Honduras	Tegucigalpa	1.24
Mexico	Ciudad Juarez	0.62
	Guadalajara	1.24
	Hermosillo	1.24
	Matamoros	0.06
	Mazatlan	0.60
	Merida	0.06
	Mexico City	1.24
	Monterrey	0.06
	Nuevo Laredo	0.06
	Tijuana	1.24
Nicaragua	Managua	1.65
Panama	Colon	1.24
	Galeta	0.83
Europe		
Albania	Tirana	1.24
Austria	Salzburg	0.62
	Vienna	0.62
Belgium	Antwerp	0.31
	Brussels	0.62
Bulgaria	Sofia	1.24
Croatia	Zagreb	1.24
Czech Republic	Bratislava	0.62
	Prague	0.31
Denmark	Copenhagen	0.31
Finland	Helsinki	0.31
France	Bordeaux	0.62
	Lyon	0.31
	Marseille	1.24
	Nice	1.24
	Strasbourg	0.62
Germany	Berlin	0.06
	Bonn	0.62
	Bremen	0.06
	Dusseldorf	0.31
	Frankfurt	0.62
	Hamburg	0.06
	Munich	0.31
	Stuttgart	0.62
	Vaihingen	0.62
Greece	Athens	1.24
	Kavalla	1.65
	Makri	1.65
	Rhodes	1.24
	Sauda Bay	1.65
	Thessaloniki	1.65
Hungary	Budapest	0.62
Iceland	Keflavik	1.24
	Reykjavik	1.65
Ireland	Dublin	0.06
Italy	Aviano AFB	1.24
	Brindisi	0.06
	Florence	1.24
	Genoa	1.24
	Milan	0.62
	Naples	1.24
	Palermo	1.24
	Rome	0.62
	Sicily	1.24
	Trieste	1.24
	Turin	0.62
Luxembourg	Luxembourg	0.31
Malta	Valletta	0.62
Netherlands	All	0.06
Norway	Oslo	0.62
Poland	Krakow	0.62
	Poznan	0.31
	Waraszawa	0.31
Portugal	Lisbon	1.65
	Oporto	1.24
Romania	Bucharest	1.24
Russia	Moscow	0.06
	St. Petersburg	0.06
Serbia	Belgrade	0.62
Spain	Barcelona	0.62
	Bilbao	0.62
	Madrid	0.06
	Rota	0.62
	Seville	0.62
Sweden	Goteborg	0.62
	Stockholm	0.31
Switzerland	Bern	0.62
	Geneva	0.31
	Zurich	0.62
Ukraine	Kiev	0.06
United Kingdom	Belfast	0.06
	Edinburgh	0.31
	Glasgow/Renfrew	0.31
	Hamilton	0.31
	Liverpool	0.31
	London	0.62
	Londonderry	0.31
	Thurso	0.31
North America		
Greenland	All	0.31
Canada	Argentia NAS	0.62
	Calgary, AB	0.31
	Churchill, MB	0.06
	Cold Lake, AB	0.31
	Edmonton, AB	0.31
	E. Harmon, AFB	0.62
	Fort Williams, ON	0.06
	Frobisher, NT	0.06
	Goose Airport	0.31
	Halifax, NS	0.31
	Montreal, QC	1.24
	Ottawa, ON	0.62
	St. John's, NL	1.24
	Toronto, ON	0.31
	Vancouver, BC	1.24
	Winnipeg, MB	0.31
South America		
Argentina	Buenos Aires	0.25
Brazil	Belem	0.06
	Belo Horizonte	0.06
	Brasilia	0.06
	Manaus	0.06
	Porto Alegre	0.06
	Recife	0.06
	Rio de Janeiro	0.06
	Salvador	0.06
	Sao Paulo	0.31
Bolivia	La Paz	1.24
	Santa Cruz	0.31
Chile	Santiago	1.65
	Valparaiso	1.65
Colombia	Bogota	1.24
Ecuador	Quito	1.65
	Guayaquil	1.24
Paraguay	Asuncion	0.06
Peru	Lima	1.65
	Piura	1.65
Uruguay	Montevideo	0.06
Venezuela	Maracaibo	0.62
	Caracas	1.65
Pacific Ocean Area		
Australia	Brisbane	0.31
	Canberra	0.31
	Melbourne	0.31
	Perth	0.31
	Sydney	0.31
Caroline Islands	Koror, Palau	0.62
	Ponape	0.06
Fiji	Suva	1.24
Johnson Island	All	0.31
Mariana Islands	Guam	1.24
	Saipan	1.24
	Tinian	1.24
Marshall Islands	All	0.31
New Zealand	Auckland	1.24
	Wellington	1.65
Papau New Guinea		
	Port Moresby	1.24
Phillipine Islands	Cebu	1.65
	Manila	1.65
	Bagulo	1.24
Samoa	All	1.24
Wake Island	All	0.06

The nominal weight component at each restraint is simply the total operating weight divided by the number of restraints. This is always directed downward when summing forces and is computed using Equation (16).

The vertical seismic force is simply the weight component at each location multiplied by the vertical seismic force factor in terms of the total F_{pv} load expressed in gs, the gravitational constant (F_{pv}/W_p, where F_{pv} is the vertical seismic load component as defined by the code and W_p is the total operating weight of the equipment). This can be directed either upward or downward when summing forces. The actual value of this load at a given restraint point is defined by Equations (9a), (9b), and (9c). Assuming the simple case, $F_{pv} = F_p/3$, and results in a nominal load at the restraint of

$$T_n = \pm W_n F_{pv}/W_p \qquad (18)$$

where T_n and W_n are tensile and gravity loads at particular restraint points.

The overturning force at a restraint is highly dependent on the direction of the seismic wave front. In the polar method, first determine a worst-case load angle and load. This is then summed with the other worst-case loads to determine a worst-case combination load.

The worst-case approach angle for the seismic wave front is a function of the length and width of the restraint. If we assume a dimension of A between the outermost restraints on the long axis and a dimension B between the outermost restraints on the short axis, then the worst-case angle for the seismic load relative to the long axis centerline is

$$\theta = \arctan(B/A) \qquad (19)$$

The stabilizing factor that results from multiple restraints aligned along the long axis is

$$I_x = 2(\text{No. of restraints on } y\text{-axis side})(B/2)^2 \qquad (20)$$

and along the short axis is

$$I_y = 2(\text{No. of restraints on } x\text{-axis side})(A/2)^2 \qquad (21)$$

From Figure 3, F_p (total lateral seismic force), and h_{cg} (height of equipment center of gravity above point of restraint), the maximum force generated at a corner restraint by overturning is

$$T_m = \pm\left\{F_p\left[\left(\frac{Bh_{cg}}{I_x}\right)\cos\theta + \left(\frac{Ah_{cg}}{I_y}\right)\sin\theta\right]\right\} \qquad (22)$$

This can be directed either upward or downward to produce a worst case when summing forces.

$$T_{eff} = -W_n + T_n + T_m \qquad (23)$$

Lump Mass Method

In the lump mass method, the total equipment weight is distributed among the restraints in a manner that reflects the equipment's actual weight distribution. There are many methods of determining the distribution analytically or by testing, although they are not addressed in this section. Frequently, a weight distribution can be obtained from the equipment manufacturer.

Determination of Lateral Seismic Forces at Restraints. Once the static point loads are obtained or computed for each restraint location, they can be multiplied by the lateral seismic acceleration factor (F_p/W_p) to determine lateral forces at each restraint point. Thus, if the weight at each restraint point is W_n, then

$$V_{eff} = (F_p/W_p)W_n \qquad (24)$$

Determination of Vertical Seismic Forces at Restraints. This method considers the loads at all the restraints individually and computes the overturning forces for each in 1° increments for a full 360° of possible seismic wave front angle; it is only practical to perform using a spreadsheet. The total lateral seismic force F_p is divided into x- and y-axis components for each possible wave front approach angle. These forces are multiplied by the height of the equipment center of gravity above the point of restraint h_{cg}. The resulting moments are then resolved into forces at each restraint based on the x- and y-axis moment arms associated with the particular restraint location and the proportion of the load that it will bear. For example, with four total restraints (one at each corner), two per side, each restraint will generate half the uplift force generated in resisting an x- or y-axis moment. If there are additional restraints at the equipment midpoint (six restraints total and the resistant force is proportional to the moment arm), for long-axis moments, each corner restraint will contribute 4/10 of the resisting moment and each center restraint will contribute 1/10 of the resisting moment. The x- and y-axis values are then summed to determine the total resulting force for the restraint at each load angle increment. Once forces for all angles from 0 to 360° have been computed, the worst-case load at each point can be identified.

Equations (25) through (29) are used to compute the overturning load for the case illustrated in Figure 3. They should be repeated for each restraint and for each seismic wave front angle θ from 0 to 360° with the maximum and minimum final values selected.

$$F_{px} = F_p(-\cos\phi) \quad F_{py} = F_p(-\sin\phi) \qquad (25)$$

$$T_{mx} = F_{px}h_{cg}/(2D_1) \quad T_{my} = F_{py}h_{cg}/(2D_2) \qquad (26)$$

where D_1 and D_2 are the spacing between restraints on the long and short axis, respectively.

$$T_m = T_{mx} + T_{my} \qquad (27)$$

Because the total vertical seismic force is the total weight multiplied by the vertical seismic force factor in g, the vertical seismic force at any particular restraint is

$$T_n = \pm W_n F_{pv}/W_p \qquad (28)$$

and the total vertical force component is

$$T_{eff} = -W_n + T_m + T_n \qquad (29)$$

Positive (+) loads that result from these equations are identified as upward. Negative (–) loads are directed downward.

Resilient Support Factors

If the equipment being restrained is isolated, the following three factors must be considered:

• For all forces that are not directed along the principal axes, only the corner restraints can be considered to be effective. Thus, for either distribution method, only the corner restraints can be considered capable of absorbing vertical loads.

• If the restraints are independent (separate entities) from the spring isolation elements and if, when exposed to uplift loads, vertical spring forces are not absorbed within the housing of an integral isolator/restraint assembly, the weight factor determined in the first step of the vertical load analysis should be ignored. (This is because any effect that a weight reduction has on the attachment hardware forces is replaced by an approximately equal vertical force component from the spring.)

• If the 2000 IBC is used, the final computed forces must be doubled.

Interaction of Attachment Hardware Shear and Tensile Forces. The two most common attachment arrangements are directly bolting the equipment or restraint or anchoring it to concrete using post-installed (not cast in place) anchors. To evaluate the combined

effective tensile and shear forces that act simultaneously on these connections, separate analyses are required.

Note that for short-term wind or seismic loads, the codes or fastener evaluation report may permit the allowable stresses for either bolted-to-steel or anchored-to-concrete connections to be increased by a factor of 1.33 (*California applications involving hospitals and schools have special requirements and should be reviewed by a California registered engineer*). If allowable stress design (ASD) data are used to size hardware for bolt-to-steel connections for 1997 UBC or 2000 IBC code applications, the loads may be reduced by a factor of 1.4. If load and resistance factor (LRF) criteria is used for the hardware, the 1.4 factor does not apply. The allowable stresses to be used when evaluating anchor bolts are drawn from ICBO test reports and reflect values that are considerably derated from values typically published by anchor manufacturers. Also note that the values published by ICBO for concrete anchors are working-stress based and in that form are incompatible with the 1997 UBC and 2000 IBC, which generate strength-based loads. Before computing interaction forces, the computed loads for these newer codes must be reduced by a factor of 1.4 to make them compatible. The 1.4 factor does not apply when working with the older codes.

For direct attachment to a 1994 UBC or older steel structure with through bolts, the design capacity of the attachment hardware should be based on criteria established in the American Institute of Steel Construction (AISC) manual. Based on the use of A307 bolts, the basic formula for computing allowable tensile stress when shear stresses are present is

$$T_{allow} = 26,000 - 1.8 S_v \qquad (30)$$

where S_v is the shear stress in the bolt in psi. T_{allow}, the maximum allowable tensile stress, must not exceed 20,000 psi.

However, because these stresses are appropriate for dead- plus live-load combinations, they can be appropriately inflated by 1.33 when allowable stress design provisions are used and when they are used to resist wind and seismic loads as well. Peak bolt loads are based on the maximum permitted stress multiplied by the nominal bolt area.

For attachment to concrete using post-installed anchors, the 1997 UBC requires that seismic forces be doubled for isolated systems. This additional factor has been included in Table 6. On the other hand, because published post-installed anchor capacities are working-stress based, the strength-based forces predicted by the 2000 IBC or the 1997 UBC can be reduced by a factor of 1.4 when evaluating the integrity of the connection.

The interaction formula for concrete anchors is

$$(T_{eff}/T_{allow})^{5/3} + (V_{eff}/V_{allow})^{5/3} \leq 1 \qquad (31)$$

where

    T_{eff} = tensile load at anchor
    T_{allow} = maximum allowable anchor tensile load
    V_{eff} = shear load at anchor
    V_{allow} = maximum allowable anchor shear load

LAG SCREWS INTO TIMBER

Acceptable loads for lag screws into timber can be obtained from the *National Design Specification*® (NDS®) *for Wood Construction* (AWC 1997). Selected fasteners must be secured to solid lumber, not to plywood or other similar material. Withdrawal force design values are a function of the screw size, penetration depth, and wood density and can be increased by a factor of 1.6 for short-term seismic or wind loads. Table 9.2A in the NDS identifies withdrawal forces on a force/imbedment depth basis. Note that the values published in the table are working-stress based and in that form are incompatible with the 1997 UBC and 2000 IBC, which generate strength-based loads. Before computing interaction

forces, the computed loads for these newer codes must be reduced by a factor of 1.4 to make them compatible. The 1.4 factor does not apply when working with the older codes. In addition, NDS Table 9.4.2 introduces deration factors for reduced edge distance and bolt spacing.

In timber construction, the interaction formula given in Equation (15) does not apply. Instead, per Section 9.3.5 of the NDS, the equation is

$$Z_a' = (W'p)Z'/[(W'p)\cos^2\alpha + Z'\sin^2\alpha]$$

where

    Z' = shear capacity drawn from Table 9.3A
    W' = side grain withdrawal force = $1800G^{3/2}D^{3/4}$
    G = specific gravity of the timber
    D = diameter
    p = embedment depth of screw
    α = angle of composite force measured flat with surface of timber

ANCHOR BOLTS

Several types of anchor bolts for insertion in concrete are manufactured. Wedge and undercut anchors perform better than self-drilling, sleeve, or drop-in types. **Adhesive anchors** are stronger than other anchors, but lose their strength at elevated temperatures (e.g., on rooftops and in areas damaged by fire).

Wedge anchors have a wedge on the end with a small clip around the wedge. After a hole is drilled, the bolt is inserted and the external nut tightened. The wedge expands the small clip, which bites into the concrete.

When **undercut anchors** are tightened, the tip expands to seat against a shoulder cut in the bottom of the anchor hole. Although these have the highest capacity of commonly available anchor types, the cost of the extra operation to cut the shoulder in the hole greatly limits the frequency of their use in the field.

A **self-drilling anchor** is basically a hollow drill bit. The anchor is used to drill the hole and is then removed. A wedge is then inserted on the end of the anchor, and the assembly is drilled back into place; the drill twists the assembly fully in place. The self-drilling anchor is weaker than other types because it forms a rough hole.

Drop-in expansion anchors are hollow cylinders with a tapered end. After they are inserted in a hole, a small rod is driven through the hollow portion, expanding the tapered end. These anchors are only for shallow installations because they have no reserve expansion capacity.

A **sleeve anchor** is a bolt covered by a threaded, thin-wall, split tube. As the bolt is tightened, the thin wall expands. Additional load tends to further expand the thin wall. The bolt must be properly preloaded or friction force will not develop the required holding force. These anchors are typically not used in seismic applications because of the limited reserve capacity.

Adhesive anchors may be in glass capsules or installed with various tools. Pure epoxy, polyester, or vinyl ester resin adhesives are used with a threaded rod supplied by the contractor or the adhesive manufacturer. Some adhesives have a problem with shrinkage; others are degraded by heat. However, some adhesives have been tested without protection to 1100°F before they fail (all mechanical anchors will fail at this temperature). Where required, or if there is a concern, anchors should be protected with fire retardants similar to those applied to steel decks in high-rise buildings.

The manufacturer's instructions for installing the anchor bolts should be followed. Performance test data published by manufacturers should include shock, fatigue, and seismic resistance. ICBO reports have further information on allowable forces for design. Use a safety factor of 2 if the installation has not been inspected by a qualified firm or individual.

WELD CAPACITIES

Weld capacities may be calculated to determine the size of welds needed to attach equipment to a steel plate or to evaluate raised support legs and attachments. A static analysis provides the effective tension and shear forces. The capacity of a weld is given per unit length of weld based on the shear strength of the weld material. For steel welds, the allowable shear strength capacity is 16,000 psi on the throat section of the weld. The section length is 0.707 times the specified weld size.

For a 1/16 in. weld, the length of shear in the weld is $0.707 \times 1/16 = 0.0442$ in. The allowable weld force $(F_w)_{allow}$ for a 1/16 in. weld is

$$(F_w)_{allow} = 0.0442 \times 16,000 = 700 \text{ lb per inch of weld}$$

For a 1/8 in. weld, the capacity is 1400 lb/in.

The effective weld force is the sum of the vectors calculated in Equations (11) and (13), (17) and (23), or (24) and (29). Because the vectors are perpendicular, they are added by the method of the square root of the sum of the squares (SRSS), or

$$(F_w)_{allow} = \sqrt{(T_{eff})^2 + (V_{eff})^2}$$

The length of weld required is given by the following equation:

$$\text{Length} = (F_w)_{eff}/(F_w)_{allow} \tag{32}$$

SEISMIC SNUBBERS

Several types of snubbers are manufactured or field fabricated. All snubber assemblies should meet the following minimum requirements to avoid imparting excessive accelerations to HVAC&R equipment:

- Impact surface should have a high-quality elastomeric surface that is not cemented in place.
- Resilient material should be easy to inspect for damage and be replaceable.
- Snubber system must provide restraint in all directions.
- Snubber capacity should be verified either through test or by analysis and should be certified by an independent, registered engineer to avoid serious design flaws.

Typical snubbers are classified as Types A through J (Figure 4).

Type A. Snubber built into a resilient mounting. All-directional, molded bridge-bearing quality neoprene element is a minimum of 1/8 in. thick.

Type B. Isolator/restraint. Stable isolation spring bears on the base plate of the fixed restraining member. Earthquake motion of isolated equipment is restrained close to the base plate, minimizing pullout force to the base plate anchorage.

Type C. Spring isolator with built-in all-directional restraints. Restraints have molded neoprene elements with a minimum thickness of 1/8 in. A neoprene sound pad should be installed between the spring and base plate. Sound pads below the base plate are not recommended for seismic installations.

Type D. Integral all-directional snubber/restrained spring isolator with neoprene element.

Type E. Fully bonded neoprene mount capable of withstanding seismic loads in all directions with no metal-to-metal contact.

Type F. All-directional three-axis snubber with neoprene element. Neoprene element of bridge-bearing quality is a minimum of 3/16 in. thick. Snubber must have a minimum of two anchor bolt holes.

Type G. All-directional lateral snubber. Neoprene element is a minimum of 1/4 in. thick. Upper bracket is welded to the equipment.

Type H. Restraint for floor-mounted equipment consisting of interlocking steel assemblies lined with resilient elastomer. Bolted

to equipment and anchored to structure through slotted holes to allow field adjustment. After final adjustment, weld anchor to floor bracket and weld angle clip to equipment or, alternatively, fill slots with adhesive grout to prevent slip.

Type I. Single-axis, single-direction lateral snubber. Neoprene element is a minimum of 1/4 in. thick. Minimum floor mounting is with two anchor bolts. Must be used in sets of four or more.

Type J. Prestretched aircraft wire rope with galvanized end connections that avoid bending the wire rope across sharp edges. This type of snubber is mainly used with suspended pipe, ducts, and equipment.

EXAMPLES

The following examples are provided to assist in the design of equipment anchorage to resist seismic forces. For Examples 1 through 4, assume 2000 IBC applies, $I_p = 1.5$, $S_s = 0.85$, site soil class is C, and the equipment is located at the top of a 50 ft building. Also include an uplift force component $F_{pv} = 0.2S_{DS}D$ where D is the dead load for all examples. Examples 1 through 5 are solved using the polar method of analysis while Example 6 is solved by the lump mass method.

Example 1. Anchorage design for equipment rigidly mounted to the structure (see Figure 5).

From Equations (1) through (3) and (9), calculate the lateral seismic force and its vertical component. Note that for expansion anchors, $R_p = 1.5$; for other cases, $R_p = 2.5$. For attachment to wood or steel, the seismic loads are initially determined using the 2.5 factor. For attachment to concrete with post-installed anchors, the 1.5 factor is used and an embedment depth of over 8 bolt diameters is assumed. For rigidly mounted mechanical equipment, a_p from Table 3 is 1.0.

The first step in the load determination process is to determine S_{DS} using the following equation and $F_a = 1.1$ (from Table 4, site class C):

$$S_{DS} = 2F_aS_s/3 = 2 \times 1.1 \times 0.85/3 = 0.623$$

Using this value for S_{DS} Equation (1) gives

$$F_p = [(0.4 \times 1.0 \times 0.623 \times 1000)/(2.5/1.5)] (1 + 2 \times 50/50) = 450 \text{ lb}$$
$$\text{(steel/wood anchorage)}$$

$$F_p = [(0.4 \times 1.0 \times 0.623 \times 1000)/(1.5/1.5)] (1 + 2 \times 50/50) = 750 \text{ lb}$$
$$\text{(concrete anchorage)}$$

Equation (2) shows that F_p need not be greater than

$$1.6 \times 0.85 \times 1.5 \times 1000 = 2040 \text{ lb}$$

Equation (3) shows that F_p must not be less than

$$0.3 \times 0.85 \times 1.5 \times 1000 = 383 \text{ lb}$$

Therefore $F_p = 450$ lb for attachment to steel or wood and 750 lb for attachment to concrete.

$$F_{pv} = 0.2S_{DS}D = 0.2 \times 0.623 \times 1000 = 125 \text{ lb}$$

For through-bolt or lag screw attachment, the attachment forces are as follows:

Calculate the overturning moment OTM:

$$\text{OTM} = F_p h_{cg} = (450 \times 40) = 18,000 \text{ in·lb} \tag{33}$$

Calculate the resisting moment RM:

$$\text{RM} = (W_p \pm F_{pv})d_{min}/2 = (1000 \pm 125)28/2 = 15,750 \text{ or } 12,250 \text{ in·lb} \tag{34}$$

Calculate the tension force T, using RM_{min} to determine the maximum tension force:

$$T = (\text{OTM} - \text{RM}_{min})/d_{min} = (18,000 - 12,250)/28 = 205 \text{ lb} \tag{35}$$

This force is the same as that obtained using Equation (12).

Fig. 4   Seismic Snubbers

W_p = 1000 lb h_{cg} = 40 in. d_1 = 48 in. d_2 = 28 in.
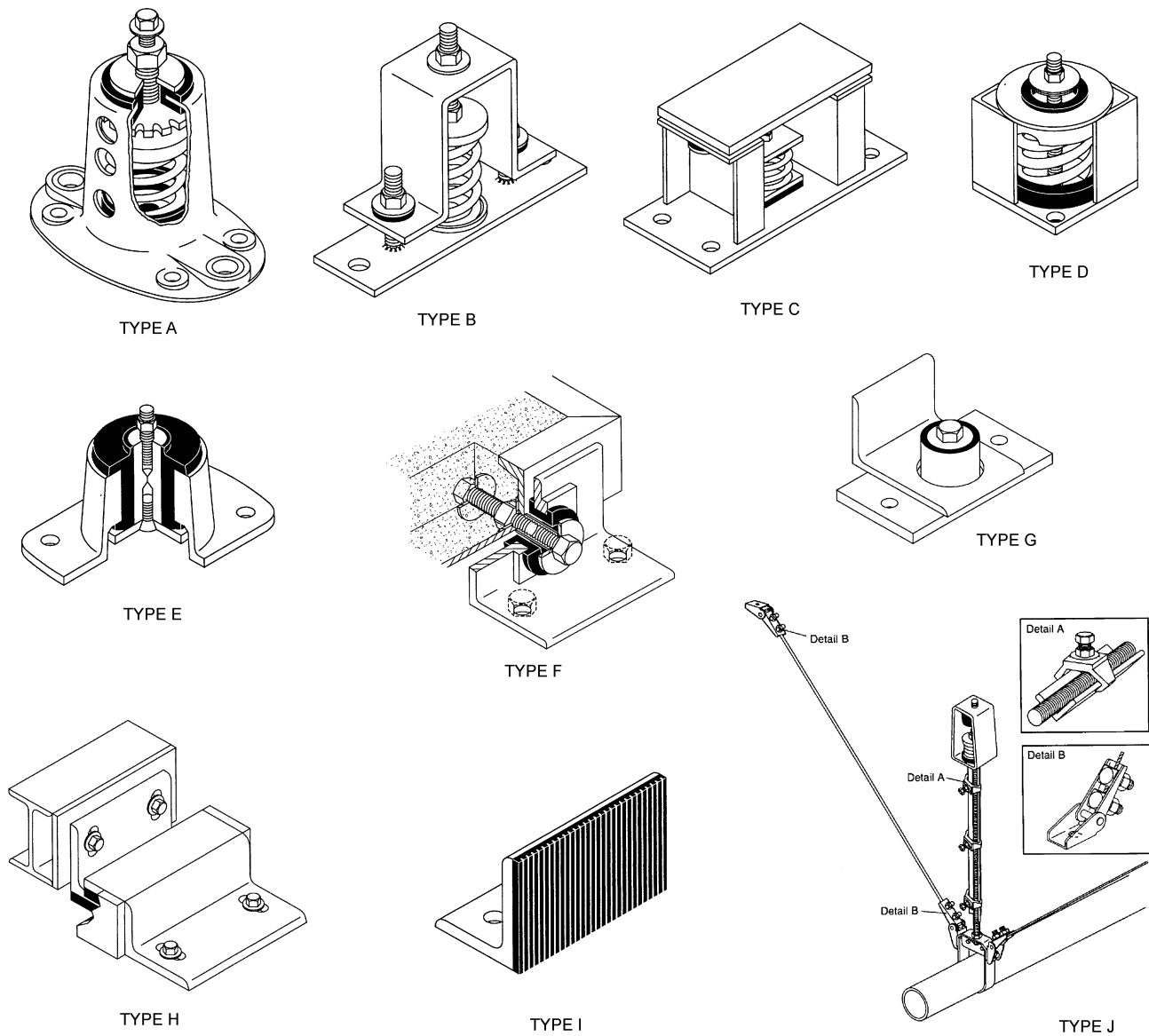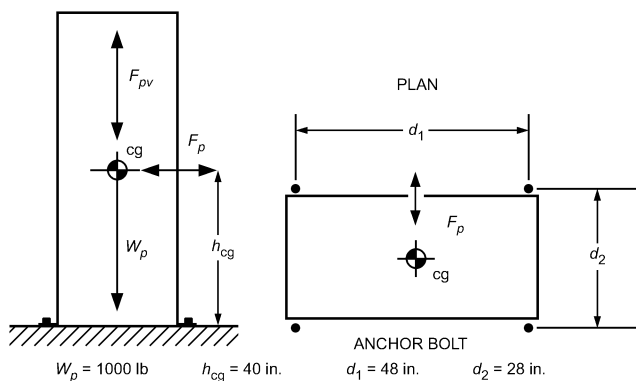
Fig. 5   Equipment Rigidly Mounted to Structure (Example 1)

Calculate T_{eff} per bolt from Equation (13):

$$T_{eff} = 205/2 = 103 \text{ lb per through-bolt or lag screw}$$

Calculate shear force per bolt from Equation (11):

$$V_{eff} = 450/4 = 112.5 \text{ lb per through-bolt or lag screw}$$

For post-installed anchor bolts, the attachment forces are computed in the same manner, using $F_p = 750$ lb instead of 450 lb:

The resulting $T_{eff} = 317$ lb and $V_{eff} = 187.5$ lb (post-installed anchor bolt)

(*Note*: Per 1621.3.12.2 of the 2000 IBC, if over 10 hp, the use of an undercut anchor bolt is required.)

Step Case 1. *Equipment attached to a timber structure*

Before computing interaction forces, the computed loads must be reduced by a factor of 1.4 to make them compatible with the capacity data listed in the *National Design Specification*® (*NDS*®) *for Wood Construction* (AWC 1997). The lateral load V_{eff} becomes 112.5/1.4 or 80.4 lb per bolt and the pullout load T_{eff} becomes 103/1.4 = 73.5 lb per bolt. For the capacity of the connection, a resulting combined load and angle relative to the mounting surface must be computed. The combined load is

$$T\alpha_{eff} = \sqrt{V_{eff}^2 + T_{eff}^2} = \sqrt{80.4^2 + 73.5^2} = 109 \text{ lb}$$

The angle $\alpha = \arcsin(T_{eff}/Z'_\alpha) = 42.5°$, where Z' is the allowable lag screw load multiplied by applicable factors and Z'_α is the factored allowable lag screw load at angle α from the mounting surface.

Selected fasteners must be secured to solid lumber, not to plywood or other similar material. The following calculations are made to determine whether a 1/2 in. diameter, 4 in. long lag screw in redwood will hold the required load. For this computation, it is assumed that bolt spacing, edge distance, temperature, and other factors do not reduce the bolt capacity (see NDS for further details) and that the load allowable factor for short-term wind or seismic loads is 1.6.

From Table 9.3A in the NDS, for redwood, $G = 0.37$, and Z perpendicular to the grain is 512 lb.

From Table 9.2A in the NDS, for $G = 0.37$ and 3.5 in. full thread, $W = 385 \times 3.5 = 1350$ lb

Substituting into the combined load equation

$$Z'_\alpha = \frac{(W'_p)Z'}{(W'_p)\cos^2\alpha + Z'\sin^2\alpha}$$

gives

$$Z'_\alpha = \frac{(385 \times 3.5)512}{(385 \times 3.5)\cos^2 42.5 + (512)\sin^2(42.5)} = 714 \text{ lb}$$

$$T\alpha_{eff}/Z'_\alpha = 109/714 = 0.15 < 1.0$$

Therefore, a 1/2 in. diameter, 4 in. long lag screw can be used at each corner of the equipment.

Step Case 2. *Equipment attached to concrete with post-installed anchors*

As determined previously,

$$T_{eff} = 317 \text{ lb per bolt and } V_{eff} = 187.5 \text{ lb per bolt}$$

Because these loads are strength based (2000 IBC and 1997 UBC) and published ICBO anchor allowables are stress based, the loads can be reduced by a factor of 1.4 to bring the data into alignment with the computation. The net result and figures used to complete the analysis are

$$T_{eff} = 317/1.4 = 226 \text{ lb per bolt}$$

and

$$V_{eff} = 187.5/1.4 = 134 \text{ lb per bolt}$$

It is good design practice to specify a minimum of 1/2 in. diameter bolts to attach roof- or floor-mounted equipment to the structure. Determine whether 1/2 in. wedge anchors without special inspection provisions will hold the required load.

From Table 14, $T_{allow} = 600$ lb and $V_{allow} = 1200$ lb

From Equation (15),

$$(317/600)^{5/3} + (134/1200)^{5/3} = 0.37 < 1.0$$

Therefore, 1/2 in. diameter, 4 in. long post-installed anchors can be used. If special inspection of the anchor installation is provided by qualified personnel, T_{allow} only may be increased by a factor of 2.

Step Case 3. *Equipment attached to steel*

For equipment attached directly to a steel member, analysis is the same as that shown in case 1. Allowable values for the attaching bolts are given in the *Manual of Steel Construction* (AISC 1989). Values for A307 bolts are given in Table 15. Because these values are stress-based numbers, the 1.4 factor used for lag screws and post-installed anchor bolts is also applicable. If the numbers used were LRF values, the 1.4 factor would not be appropriate Also, the interaction formula in Equation (15) does not apply to steel-to-steel connections. Instead, the allowable tension load must be modified as in the following equation:

$$(T_{allow})_{mod} = F_t A_b$$

where A_b is the nominal bolt area.

In this case (with a 1/2 in. diameter bolt), from Equation (30), $V_{eff} = 187.5/1.4 = 134$, $N_{bolt} = 1$, and $A_b = 0.196$.

Table 15 Allowable Loads for A307 Bolts per AISC (1989)

Diameter, in.	T_{allow}, lb	V_{allow}, lb	A_b, in²
1/2	3900	1950	0.196
5/8	6100	3100	0.307
3/4	8800	4400	0.442
1	15,700	7900	0.785

W_p = 1000 lb h_{cg} = 40 in. a = 48 in. b = 28 in.
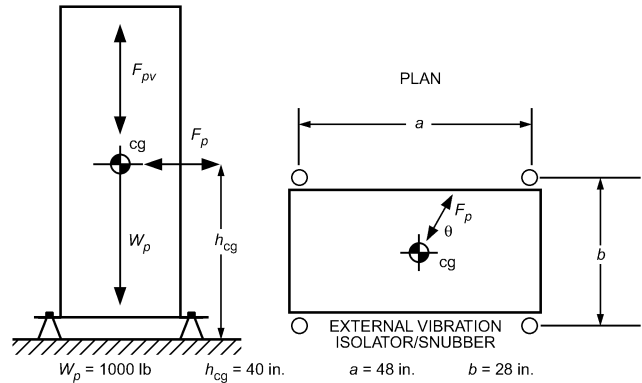
Fig. 6 Equipment Supported by External Spring Mounts

$$F_t = 26{,}000 - 1.8(V_{eff}/N_{bolt})A_b \leq 20{,}000(4/3) = 26{,}670$$

V_{eff} is in pounds and F_t is in psi. The 33% stress increase (4/3) is allowed for short-term loads such as wind or earthquakes.

$$T_{allow} = 25{,}995 \times 0.196 = 5095 > 317/1.4 = 226 \text{ lb}$$

Therefore, 1/2 in. diameter bolts can be used.

Example 2. Anchorage design for equipment supported by external spring mounts (Figure 6) and attached to concrete using nonshallow post-installed anchors.

A mechanical or acoustical consultant should choose the type of isolator or snubber or combination of the two. Then the product vendor should select the actual spring snubber.

Using the 2000 IBC, the lateral force F_p must be recalculated using new factors. S_{DS} remains as in Example 1. For expansion anchors, $R_p = 1.5$, and for resiliently mounted mechanical equipment, A_p from Table 3 is 2.5.

The basic force equation is then

$$F_p = [(0.4 \times 2.5 \times 0.623 \times 1000)/(1.5/1.5)](1 + 2 \times 50/50) = 1869 \text{ lb}$$

Equation (2) indicates that F_p need not be greater than

$$1.6 \times 0.85 \times 1.5 \times 1000 = 2040 \text{ lb}$$

Equation (3) indicates that F_p must not be less than

$$0.3 \times 0.85 \times 1.5 \times 1000 = 383 \text{ lb}$$

The vertical force F_{pv} equals

$$F_{pv} = 0.2S_{DS}D = 0.2 \times 0.623 \times 1000 = 125 \text{ lb}$$

Because the equipment is resiliently supported, section 1621.3.1 of the 2000 IBC indicates that the computed forces should be doubled. Therefore, F_p is $1869 \times 2 = 3738$ lb and F_{pv} is $125 \times 2 = 250$ lb

Assume that the center of gravity cg of the equipment coincides with the center of gravity of the isolator group.

If T = maximum tension on isolator

C = maximum compression on isolator

then

$$T = \frac{-W_p + F_{pv}}{4} + F_p h_{cg}\frac{\cos\theta}{2b} + F_p h_{cg}\frac{\sin\theta}{2a}$$

$$= \frac{-W_p + F_{pv}}{4} + \frac{F_p h_{cg}}{2}\left(\frac{\cos\theta}{b} + \frac{\sin\theta}{a}\right)$$

To find maximum T or C, set $dT/d\theta = 0$:

$$\frac{dT}{d\theta} = \frac{F_p h_{cg}}{2}\left(-\frac{\sin\theta}{b}\frac{\cos\theta}{a}\right) = 0$$

$$\theta_{max} = \tan^{-1}(b/a) = \tan^{-1}(28/48) = 30.26° \tag{36}$$

$$T = \frac{-W_p + F_{pv}}{4} + \frac{F_p h_{cg}}{2}\left(\frac{\cos\theta_{max}}{b} + \frac{\sin\theta_{max}}{a}\right) \tag{37}$$

$$C = \frac{-W_p + F_{pv}}{4} - \frac{F_p h_{cg}}{2}\left(\frac{\cos\theta_{max}}{b} + \frac{\sin\theta_{max}}{a}\right) \tag{38}$$

$$T = \frac{-1000 + 250}{4} + \frac{3738 \times 40}{2} \times \left(\frac{\cos 30.26}{28} + \frac{\sin 30.26}{48}\right) = 2908 \text{ lb}$$

$$C = \frac{-1000 + 250}{4} - \frac{3738 \times 40}{2} \times \left(\frac{\cos 30.26}{28} + \frac{\sin 30.26}{48}\right) = -3408 \text{ lb}$$

Calculate the shear force per isolator:

$$V = (F_p/N_{iso}) = 3738/4 = 935 \text{ lb} \tag{39}$$

This shear force is applied at the operating height of the isolator. Uplift tension T on the vibration isolator is the worst condition for the design of the anchor bolts. The compression force C must be evaluated to check the adequacy of the structure to resist the loads (Figure 7).

$$(T_1)_{eff} \text{ per bolt} = T/2 = 2908/2 = 1454 \text{ lb}$$

The value of $(T_2)_{eff}$ per bolt due to overturning on the isolator is

$$(T_2)_{eff} = \frac{V \times \text{Operating height}}{d N_{bolt}}$$

where d is the distance from edge of isolator base plate to center of bolt hole.

$$(T_2)_{eff} = (1454 \times 8)/(3 \times 2) = 1939 \text{ lb}$$

$$(T_{max})_{eff} = (T_1)_{eff} + (T_2)_{eff} = 1454 + 1939 = 3393 \text{ lb}$$

$$V_{eff} = 935/2 = 468 \text{ lb}$$

Determine whether 5/8 in. post-installed anchors *with special inspection* will handle this load. From Equation (15) and Table 9,

$$\left(\frac{3393}{2 \times 900}\right)^{5/3} + \left(\frac{468}{2200}\right)^{5/3} = 2.95 > 1.0$$

Therefore, 5/8 in. post-installed anchors will not carry the load.

Example 3. Anchorage design for equipment with a center of gravity different from that of the isolator group (Figure 8).

Anchor properties $I_x = 4B^2; \quad I_y = 4L^2$

Angles $\theta = \tan^{-1}(B/L) \tag{40}$

$$\alpha = \tan^{-1}(e_x/e_y) \tag{41}$$
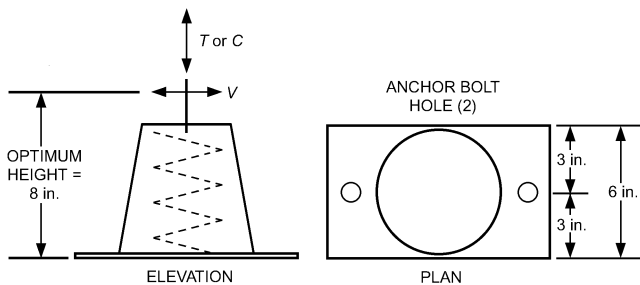
Fig. 7 Spring Mount Detail (Example 2)

$$\beta = 180 |\alpha - \theta| \tag{42}$$

$$\phi = \tan^{-1}(LI_x/BI_y) \tag{43}$$

Vertical reactions

$$(W_n)_{max/min} = W_p \pm F_{pv} \tag{44}$$

Vertical reaction caused by overturning moment

$$T_m = \pm F_p\left(\frac{Bh_{cg}}{I_x}\cos\phi + \frac{Lh_{cg}}{I_y}\sin\phi\right) \tag{45}$$

Vertical reaction caused by eccentricity

$$(T_e)_{max/min} = (W_n)_{max/min}\left(\frac{Be_y}{I_x} + \frac{Le_x}{I_y}\right) \tag{46}$$

Vertical reaction caused by W_p

$$(T_w)_{max/min} = (W_n)_{max/min}/4 \tag{47}$$

$$T_{max} = T_m + (T_e)_{max} + (T_w)_{max} \text{ (always compression)} \tag{48}$$

$$T_{min} = -T_m + (T_e)_{min} + (T_w)_{min} \text{ (tension if negative)} \tag{49}$$

Horizontal reactions

Horizontal reaction caused by rotation

$$V_{rot} = F_p\left[\frac{e_x^2 + e_y^2}{16(B^2 + L^2)}\right]^{0.5} \tag{50}$$

$$V_{dir} = F_p/4 \tag{51}$$

$$V_{max} = (V_{rot}^2 + V_{dir}^2 - 2V_{rot}V_{dir}\cos\beta)^{0.5} \tag{52}$$

For isolated equipment attachment to steel, Equation (1) gives

$$F_p = 0.4 \times 2.5 \times 0.623 \times 2500 \times \frac{1.5}{2.5}\left(1 + 2 \times \frac{50}{50}\right) = 2804 \text{ lb}$$

Equation (2) indicates that F_p need not be greater than

$$1.6 \times 0.85 \times 1.5 \times 2500 = 5100 \text{ lb}$$

Equation (3) indicates that F_p must not be less than

$$0.3 \times 0.85 \times 1.5 \times 2500 = 956 \text{ lb}$$

The vertical force F_{pv} is

$$F_{pv} = 0.2S_{DS}D = 0.2 \times 0.623 \times 2500 = 312 \text{ lb}$$
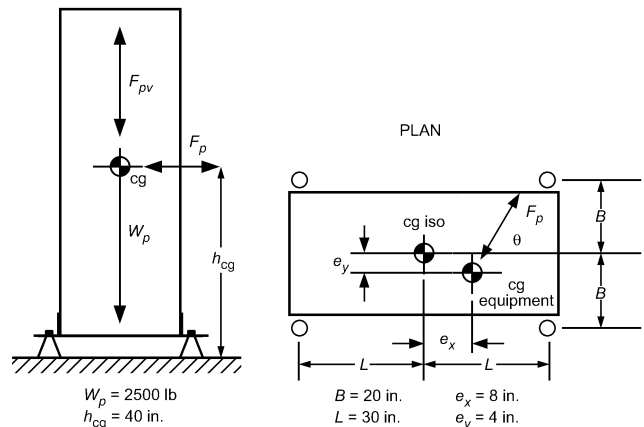
Fig. 8 Equipment with Center of Gravity Different from Isolator Group (in Plan View)

Doubling the result for the resilient supports gives a design F_p of 5608 lb and F_{pv} of 624 lb.

Anchor properties are

$$I_x = 4(20)^2 = 1600$$

$$I_y = 4(30)^2 = 3600$$

From Equations (40) through (43),

$\theta = 33.69°$	$\alpha = 63.43°$
$\beta = 150.26°$	$\phi = 33.69°$

From Equation (44),

$$(W_n)_{max/min} = 2500 \pm 624 = 3124 \text{ lb or } 1876 \text{ lb}$$

From Equation (45),

$$T_m = \pm 5608(0.416 + 0.184) = \pm 3365 \text{ lb}$$

From Equation (46),

$$(T_e)_{max/min} = 0.1167(W_n)_{max/min} = 365 \text{ lb or } 219 \text{ lb}$$

From Equation (47),

$$(T_w)_{max/min} = 781 \text{ lb or } 469 \text{ lb}$$

From Equation (48),

$$T_{max} = 3365 + 365 + 781 = 4511 \text{ lb}$$

From Equation (49),

$$T_{min} = -3365 + 219 + 469 = -2677 \text{ lb (tension)}$$

From Equations (50), (51), and (52),

$$V_{rot} = 5608 \times 0.062 = 348 \text{ lb}$$

$$V_{dir} = 5608/4 = 1402 \text{ lb}$$

$$V_{max} = 1713 \text{ lb}$$

The values of T_{min} and V_{max} are used to design the anchorage of the isolators and/or snubbers, and T_{max} is used to verify the structure's adequacy to resist the vertical loads.

Example 4. Anchorage design for equipment with supports and bracing for suspended equipment (Figure 9). Equipment weight $W_p = 500$ lb.

Because post-installed anchors may not withstand published allowable static loads when subjected to vibratory loads, vibration isolators should be used between the equipment and the structure to damp vibrations generated by the equipment.

For attachment to steel and isolated equipment, Equation (1) gives

$$F_p = 0.4 \times 2.5 \times 0.623 \times 500 \times \frac{1.5}{2.5}\left(1 + 2 \times \frac{50}{50}\right) = 561 \text{ lb}$$

Equation (2) indicates that F_p need not be greater than

$$1.6 \times 0.85 \times 1.5 \times 500 = 1020 \text{ lb}$$

Equation (3) indicates that F_p must not be less than

$$0.3 \times 0.85 \times 1.5 \times 500 = 191 \text{ lb}$$

The vertical force F_{pv} is

$$F_{pv} = 0.2 S_{DS} D = 0.2 \times 0.623 \times 500 = 62 \text{ lb}$$

Doubling the result for the resilient supports gives a design F_p of 1122 lb and F_{pv} of 124 lb.

Anchor properties $I_x = 4B^2; I_y = 4L^2$

Angle $\phi = \tan^{-1}(LI_x / BI_y) = 36.86°$

From Equation (44),

$$(W_n)_{max/min} = 500 \pm 124 = 624 \text{ lb or } 376 \text{ lb}$$
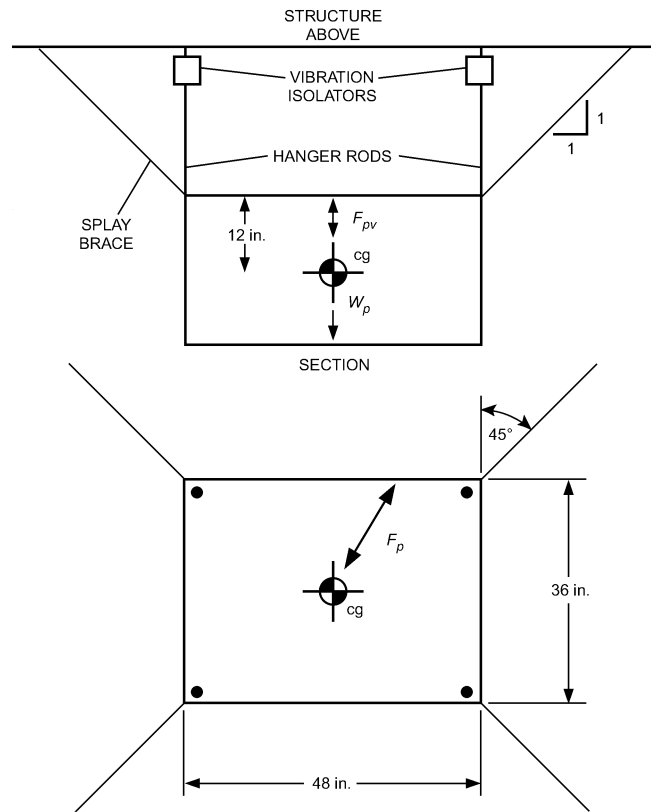
Note: Splay braces are prestretched aircraft cables with enough slack so that isolators can fully function vertically.

Fig. 9   Supports and Bracing for Suspended Equipment

From Equation (45),

$$T_m = \pm 1122 (0.132 + 0.075) = \pm 233 \text{ lb}$$

From Equation (46),

$$T_e = 0$$

From Equation (47),

$$(T_w)_{max/min} = 156 \text{ lb or } 94 \text{ lb}$$

From Equation (48),

$$(T_{eff})_{max} = 233 + 0 + 156 = 389 \text{ lb (downward)}$$

From Equation (49),

$$(T_{eff})_{min} = -233 + 0 + 94 = -139 \text{ lb (upward)}$$

Forces in the hanger rods:

Maximum tensile = 389 lb
Maximum compression = 139 lb

Force in the splay brace = $F_p \sqrt{2} = 1587$ lb at a 1:1 slope

Because of the force being applied at the critical angle, as in Example 2, only one splay brace is effective in resisting the lateral load F_p.

Design of hanger rod/vibration isolator and connection to structure

When post-installed anchors are mounted to the underside of a concrete beam or slab, the allowable tension loads on the anchors must be reduced to account for cracking of the concrete. A general rule is to use half the allowable load. Some manufacturers have ICC reports that provide allowable values for anchors installed under the slab.

Determine whether a 1/2 in. wedge anchor with special inspection provisions will hold the required load.

$$T_{allow} = 600 \times 0.5 \times 2 = 600 \text{ lb} > T_{eff} = 389 \text{ lb}$$

Therefore, a 1/2 in. rod and post drill-in anchor should be used at each corner of the unit.

For anchors installed without special inspection,

$$T_{allow} = 600 \times 0.5 = 300 \text{ lb} < T_{eff} = 389 \text{ lb}$$

Therefore, a larger anchor should be chosen.

Determine if the 1/2 in. hanger rod would require a stiffener if it is 36 in. long.

Good practice is to not allow the compressive force to exceed 1/4 of the Euler buckling load. The Euler load can be computed using the formula

$$P_e = \frac{\pi^2 EI}{L^2} \tag{53}$$

where

- E = modulus of rod (29,000,000 psi for steel)
- I = moment of inertia ($\pi d^4/64$)
- L = rod length, in.
- d = rod diameter, in.

which gives

$$P_e = \pi^2(29,000,000 \text{ psi} \times 0.0031)/36^2 = 685 \text{ lb}$$

Because the maximum compressive load of 139 lb is less than 685 lb/4, a rod stiffener is not required.

Design of splay brace and connection to structure

Force in the slack cable = 1587 lb

Because all of the load must be resisted by a single cable, the forces in the connection to the structure are

$$V_{max} = 1122 \text{ lb} \qquad T_{max} = F_p = 1122 \text{ lb}$$

Determine whether a 3/4 in. wedge anchor will hold the required load.

From Table 14,

$$T_{allow} = 1350/2 = 675 \text{ lb} \qquad V_{allow} = 3000 \text{ lb}$$

From Equation (31),

$$\left(\frac{1122}{675}\right)^{5/3} + \left(\frac{1122}{3000}\right)^{5/3} = 2.52 > 1.0$$

Therefore, it is not permissible to use a 3/4 in. anchor. A larger anchor or multiple anchors bolted through a clip and to the structure are required.

Because the cable forces are relatively small, a 3/8 in. aircraft cable attached to clips with cable clamps should be used. The clips, in turn, may be attached to either the structure or the equipment.

Example 5. Anchorage design for equipment with a center of gravity different from that of the isolator group and with six mounting points (Figure 10).

For this computation, use the 2000 IBC and a ground acceleration term S_S of 1.29. Assume that the general-purpose building ($I_p = 1$) is built on stiff soil ($F_a = 1.4$). The equipment ($a_p = 1$) is solid-mounted 2/3 of the way to the top of the building and is attached to concrete ($R_p = 1.5$). The equipment weighs 1000 lb and the specification vertical load is equal to $0.2S_{DS}D$.

To determine S_{DS}, use the equation

$$S_{DS} = \frac{2F_a S_s}{3}$$
$$= \frac{2 \times 1.4 \times 1.29}{3} = 1.21 \tag{54}$$

For both of these cases, use lateral force Equation (1):
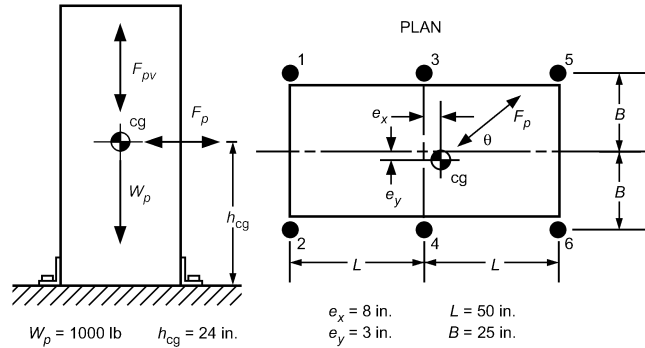
Fig. 10 **Floor-Mounted Equipment with Solid or Isolated Connection to Structure (Example 5)**

$$F_p = (0.4a_p S_{DS} W_p)\left(\frac{I_p}{R_p}\right)\left[1 + 2\left(\frac{z}{h}\right)\right]$$

where F_p need not exceed $1.6S_{DS}I_pW_p$, nor can it be less than $0.35S_{DS}I_pWp$.

Lateral design force

Inserting appropriate values into Equation (1) gives

$$F_p = (0.4 \times 1 \times 1.21 \times W_p)(1/1.5)[1 + 2(0.66)] = 0.75 \, W_p$$

where F_p need not exceed $1.6 \times 1.21 \times 1 \times W_p$ or $1.93W_p$, nor can it be less than $0.3 \times 1.21 \times 1 \times W_p$ or $0.36W_p$.

In this case,

$$F_p = 0.75 \, W_p = 0.75 \times 1000 = 750 \text{ lb} \tag{55}$$

Vertical design force

The vertical seismic load is

$$F_{pv} = 0.2 \times 1.21 \times 1000 = 0.242W_p = 242 \text{ lb} \tag{56}$$

Doubling the result for the resilient supports gives a design F_p of 1500 lb and F_{pv} of 484 lb.

For calculating maximum tension and compression loads, apply F_p as shown. To add the rotational effect of the applied load to the shear calculation, apply F_p at an angle perpendicular to r_0 where r is the radius from the geometric center to the center of gravity.

Anchor properties

$$I_x = 6B^2 = 3750 \text{ in}^2 \qquad I_y = 4L^2 = 10,000 \text{ in}^2$$

$$r_{1,2,5,6}^2 = B^2 + L^2 = 3125 \text{ in}^2 \qquad r_{3,4}^2 = B^2 = 625 \text{ in}^2$$

$$r_0 = \sqrt{e_x^2 + e_y^2} = 8.54 \text{ in.} \qquad r_{max} = \sqrt{B^2 + L^2} = 55.9 \text{ in}^2$$

$$\sum r^2 = 13,750 \text{ in}^2$$

The equation for calculating the maximum loads at any point in this system caused by bending about a specified axis (assuming that operating clearances are minimal and all load points contribute) is

$$f_b = \frac{M_z r_{max}}{I}$$

where M_z is the moment, r_{max} is the longest r_n dimension, and I is the rotational resistance factor.

For biaxial bending about two orthogonal axes, the equation becomes

$$f_b = \frac{(M_x Iy - M_y Ixy)L}{IxIy - Ixy^2} + \frac{(M_x Ix - M_x Ixy)B}{IxIy - Ixy^2}$$

When more than four load points are effective in countering rotational forces, angle θ = angle ϕ.

From Equation (43),

$$\phi = \tan^{-1}(LI_x/BI_y) \text{ and therefore } \theta = \tan^{-1}(LI_x/BI_y)$$

$$\phi = \theta = 36.87°$$

From Equation (44),

$$(W_n)_{max/min} = 1484 \text{ lb or } 516 \text{ lb}$$

From Equation (45) and setting angle θ = angle ϕ,

$$T_{my} = \pm300 \text{ lb}$$

From Equation (46),

$$(T_e)_{max/min} = 89 \text{ lb or } 31 \text{ lb}$$

Modifying Equation (47) for 6 restraints,

$$(T_w)_{max\,\S\,min} = \frac{(W_n)_{max\,\S\,min}}{6} = 247 \text{ lb or } 86 \text{ lb}$$

From Equation (48),

$$(T_{eff})_{max} = 300 + 89 + 247 = 636 \text{ lb (downward)}$$

From Equation (49),

$$(T_{eff})_{min} = -300 + 29 + 86 = -185 \text{ lb (upward)}$$

To calculate the maximum shear loads, add the direct shear loads to the rotational loads.

$$V_{dir} = F_p/6 = 250 \text{ lb}$$

$$M_z = F_p \times r_0 = 12{,}810 \text{ in·lb}$$

$$V_{rot} = \frac{M_z r_{max}}{\sum r^2} = 52 \text{ lb}$$

$$V_{max} = V_{dir} + V_{rot} = 302 \text{ lb}$$

It is slightly conservative to add these numbers linearly.

Example 6. Anchorage design for equipment with a center of gravity different from that of the isolator group using lump mass analysis format. Use the information given in Example 5.

The computed global seismic loads are the same as in Example 5 and are computed in the same manner.

The final result, assuming resilient supports, yields a design F_p of 1500 lb and F_{pv} of 484 lb.

Details on the methods used to approximate the dead-weight loads at each restraint point, based on an off-center weight distribution, are not illustrated here. There are several valid methods to do this; these loads are often available from the equipment supplier and are given for this example as follows:

Static loads by location

Loc 1 = 80 lb	Loc 2 = 101 lb
Loc 3 = 208 lb	Loc 4 = 265 lb
Loc 5 = 152 lb	Loc 6 = 193 lb

Lateral load computation

The lateral force at each location equals the seismic coefficient ($R_p = 2 \times 0.75 = 1.5$) multiplied by the weight at each location, which gives

Lateral seismic loads by location

Loc 1 = 120 lb	Loc 2 = 152 lb
Loc 3 = 312 lb	Loc 4 = 398 lb
Loc 5 = 228 lb	Loc 6 = 290 lb

Vertical load computation

First, the weight component at each location from the equipment must be accounted for. This is the W_n factor and was previously identified.

The vertical load component F_{pv} at each point is computed by multiplying the vertically applied load expressed in gs by the weight at each location. This factor is determined from Equation (56), taking into consideration the doubling of F_{pv} due to the use of resilient supports:

$$F_{pv} = 0.484 \times 1000 = 484 \text{ lb or } 0.484 \text{ g}$$

Variation due to vertical force F_{pv} by location (W_n)

Loc 1 = ±58 lb	Loc 2 = ±74 lb
Loc 3 = ±151 lb	Loc 4 = ±193 lb
Loc 5 = ±110 lb	Loc 6 = ±140 lb

To compute the overturning forces, composite forces must be computed and summed for each restraint and each possible seismic wavefront angle from 0 to 360°. The worst cases of these loads are then identified and summed with the weight components. Because this determination is suited to the use of a spreadsheet, the entire calculation is not shown here. Instead, the forces for one restraint position and one wavefront angle are computed to illustrate the procedure.

Computation for Loc 1 and wavefront angle $\phi = 30°$

The x component of the F_p force = $F_{px} = F_p(-\cos\phi)$. Therefore,

$$F_{px} = 1500(-\cos 30) = -1299 \text{ lb} \qquad (57)$$

Similarly, the y component of the F_p force = $F_{py} = F_p(-\sin\phi)$, thus

$$F_{py} = 1500(-\sin 30) = -750 \text{ lb} \qquad (58)$$

To compute the force on the restraint at Loc 1 due to the load F_{px}, first determine the share of the long-axis load that the end restraints in a system with six restraints will absorb.

To begin, sum the moments around the restraints at one end of the base and assume that the vertical force components at the other restraints are proportional to the distance from that center of rotation. If the vertical restraints have no operating clearance, the magnitude of the force for the pair of central restraints is 1/2 of that for the end restraints. In addition, the moment arm for the end restraint is twice that of the arm for the central restraints. As a result, the end restraints have four times the effect on the resisting moment as the central restraints. Because there are two restraints on each end, each restraint generates 40% of the moment. A similar analysis can be conducted for different arrangements of restraints. On the opposite axis (with only two restraints) each restraint takes 1/2 of the load. If there is sufficient clearance in the central vertical restraints, they will not come into play when the equipment "rocks" back and forth. In that case, the equipment should be evaluated as being supported on four points when computing overturning loads. In this example, minimum vertical clearance is assumed.

$$T_{mx} = F_{px}h_{cg}0.4/(2L) = -1299 \times 24 \times 0.4/(2 \times 50) = -125 \text{ lb} \qquad (59)$$

and

$$T_{my} = F_{py}h_{cg}0.5/(2B) = 750 \times 24 \times 0.5/(2 \times 25) = 180 \text{ lb} \qquad (60)$$

Combining these loads gives a total net overturning force at Loc 1 (with a seismic wavefront angle of 30°) equal to

$$T_m = T_{mx} + T_{my} = 125 + (-180) = -55 \text{ lb (upward)} \qquad (61)$$

Totaling the worst case combination of vertical loads for this location and this angle gives us

$$T_{max1} = W_{n1} + W_{u1} + T_{m1} = 80 + 58 - 55 = 83 \text{ lb (downward)} \qquad (62)$$

$$T_{min1} = W_{n1} - W_{u1} + T_{m1} = 80 - 58 - 55 = -33 \text{ lb (upward)} \qquad (63)$$

A complete analysis requires that this be repeated for each restraint and each angle from 0 to 360°.

Prescriptive provisions of IBC 2000 can be summarized as follows:

• Formulas for relative displacement of floor and ceiling can be conservatively estimated at 1% of the floor-to-ceiling height. This displacement must be used to determine the required horizontal

flexibility of the pipe, duct, or electrical connections at the equipment interface.

- Noncompact anchors with an embedment-to-bolt diameter less than 8 must reduce R_p from 2.5 to 1.5. This increases the seismic calculated force F_p by 1.66.
- In IBC 2003, using all-directional snubbers with clearance of more than 1/4 in. increases F_p by a factor of 2; in IBC 2000, this increase is for all isolated equipment.
- Component supports must be designed to accommodate component movement to prevent pounding on the structure or other components. This affects internal isolators and snubbers.
- Equipment components exposed to seismic impact forces and using nonductile housings must be designed using 25% of material yield stresses.
- Nonessential equipment, failure of which can cause essential equipment failure, must be designed as essential equipment.
- If the structure's site class is not provided in the contract documents, assume site class D, subject to change by the building official.
- Wedge anchor bolts are allowed with isolated equipment snubbers in IBC 2000 but not in IBC 2003 or NFPA *Code* 5000.
- For pipe or duct on any given run, if the distance from the bottom of the structure to the top of the support is 12 in. or less for all supports in that run, then that run does not need sway braces.
- Pipe and ducts may not be required to have sway braces, depending on size, material content, and importance factor. These conditions are defined in the code itself and SMACNA Appendix B (1998).

INSTALLATION PROBLEMS

The following should be considered when installing seismic restraints.

- Anchor location affects the required strengths. Concrete anchors should be located away from edges, stress joints, or existing fractures. ASTM *Standard* E488 should be followed as a guide for edge distances and center-to-center spacing.
- Concrete anchors should not be too close together. Adhesive anchors can be closer together than expansion anchors. Expansion anchors (self-drilling and drop-in) can crush the concrete where they expand and impose internal stresses in the concrete. Spacing of all anchor bolts should be carefully reviewed. (See manufacturer's recommendations.)
- Supplementary steel bases and frames, concrete bases, or equipment modifications may void some manufacturers' warranties. Snubbers, for example, should be properly attached to a subbase. Bumpers may be used with springs.
- Static analysis does not account for the effects of resonant conditions within a piece of equipment or its components. Because all equipment has different resonant frequencies during operation and nonoperation, the equipment itself might fail even if the restraints do not. Equipment mounted inside a housing should be seismically restrained to meet the same criteria as the exterior restraints.
- Snubbers used with spring mounts should withstand motion in all directions. Some snubbers are only designed for restraint in one direction; sets of snubbers or snubbers designed for multidirectional purposes should be used.
- Equipment must be strong enough to withstand the high deceleration forces developed by resilient restraints.
- Flexible connections should be provided between equipment that is braced and piping and ductwork that need not be braced.
- Flexible connections should be provided between isolated equipment and braced piping and ductwork.
- Bumpers installed to limit horizontal motion should be outfitted with resilient neoprene pads to soften the potential impact loads of the equipment.

- Anchor installations should be inspected; in many cases, damage occurs because bolts were not properly installed. To develop the rated restraint, bolts should be installed according to manufacturer's recommendations.
- Brackets in structural steel attachments should be matched to reduce bending and internal stresses at the joint.
- With the exception of heavy-duty clamps used to attach longitudinal restraints to piping systems, friction must not be relied on to resist any load. All connections should be positive and all holes should be tight-fitting or grouted to ensure minimal clearance at the attachment points.

WIND RESTRAINT DESIGN

Damage done to HVAC&R equipment by both sustained and gusting wind forces has increased concern about the adequacy of equipment protection defined in design documents. The following calculative procedure generates the same type of total design lateral force used in static analysis of the seismic restraint. The value determined for the design wind force F_w can be substituted for the total design lateral seismic force F_p when evaluating and choosing restraint devices.

The American Society of Civil Engineers' (ASCE) *Standard* 7-95 includes design guidelines for wind, snow, rain, and earthquake loads. Note that the equations, guidelines, and data presented here are from an earlier version of the ASCE standard and only cover nonstructural components. The current standard (2005) includes more comprehensive and rigorous procedures for evaluating wind forces and wind restraint. Refer to the latest version of ASCE *Standard* 7 adopted by the local jurisdiction.

TERMINOLOGY

Classification. Buildings and other structures are classified for wind load design according to Table 16.

Basic wind speed. The fastest mile-per-hour wind speed at 33 ft above the ground of Terrain Exposure C (see Table 17) having an annual probability of occurrence of 0.02. Data in ASCE *Standard* 7 or regional climatic data may be used to determine basic wind speeds. ASCE data do not include all special wind regions (such as mountainous terrains, gorges, and ocean promontories) where records or experience indicate that the wind speeds are higher than what is shown in appropriate wind data tables. For these circumstances, regional climatic data may be used provided that both acceptable extreme-value statistical analysis procedures were used in reducing the data and that due regard was given to the length of record, averaging time, anemometer height, data quality, and terrain exposure. One final exclusion is that tornadoes were not considered in developing the basic wind speed distributions.

Design wind force. Equivalent static force that is assumed to act on a component in a direction parallel to the wind and not necessarily normal to the surface area of the component. This force varies with respect to height above ground level.

Importance factor *I*. A factor that accounts for the degree of hazard to human life and damage to HVAC components (Table 18). For hurricanes, the value of the importance factor can be linearly interpolated between the ocean line and 100 miles inland because wind effects are assumed negligible at this distance inland.

Gust response factor *G*. A factor that accounts for the fluctuating nature of wind and the corresponding additional loading effects on HVAC components.

Minimum design wind load. The wind load may not be less than 10 lb/ft^2 multiplied by the area of the HVAC component projected on a vertical plane that is normal to the wind direction.

CALCULATIONS

Two procedures are used to determine the design wind load on HVAC components. The **analytical procedure**, described here, is the most common method for standard component shapes. The second method, the **wind-tunnel procedure**, is used in the analysis of complex and unusually shaped components or equipment located on sites that produce wind channeling or buffeting because of upwind obstructions. The analytical procedure produces design wind forces that are expected to act on HVAC components for durations of 1 to 10 s. The various factors, pressure, and force coefficients incorporated in this procedure are based on a mean wind speed that corresponds to the fastest mile-per-hour wind speed.

Analytical Procedure

The design wind force is determined by the following equation:

$$F_w = Q_z G C_f A_f \qquad (64)$$

where

F_w = design wind force, lb
Q_z = velocity pressure evaluated at height z above ground level, lb/ft^2
G = gust response factor for HVAC components evaluated at height z above ground level
C_f = force coefficient (Table 19)
A_f = area of HVAC component projected on a plane normal to wind direction, ft^2

Certain of the preceding factors must be calculated from equations that incorporate site-specific conditions that are defined as follows:

Velocity Pressure. The design wind speed must be converted to a velocity pressure that is acting on an HVAC component at a height z above the ground. The equation is

$$Q_z = 0.00256 K_z V^2 I \qquad (65)$$

where

K_z = velocity pressure exposure coefficient from Table 20
V = velocity from Figure 11, mph
I = importance factor from Table 18

Example Calculations: Analytical Procedure

The following example calculations are for a 400 ton cooling tower with dimensions shown in Figure 12:

Tower height h = 10 ft
Tower width D = 10 ft
Tower length l = 20 ft
Tower operating weight W_p = 19,080 lb
Tower diagonal dimension = $\sqrt{10^2 + 20^2}$ = 22.4 ft
Area normal to wind direction A_f = 10 × 22.4 = 224 ft^2
From Table 19; C_f = 1.0 for wind acting along diagonal with h/D = 10/10 = 1.

ALASKA NOTE:
For coastal areas and islands, use nearest contour.

LOCATION	V mph
Hawaii	105
Puerto Rico	125
Guam	170
Virgin Islands	125
American Samoa	125

SPECIAL WIND REGION

● POPULATION CENTER

Notes:
1. Values are 3 s gust speeds in mph at 33 ft above ground for Exposure C category and are associated with an annual probability of 0.02.
2. Linear interpolation between wind speed contours is permitted.
3. Islands and coastal areas shall use wind speed contour of coastal area.
4. Mountainous terrain, gorges, ocean promontories, and special wind regions shall be examined for unusual wind conditions.

Fig. 11   Wind Speed Data
Reprinted with permission from ASCE *Standard* 7-95
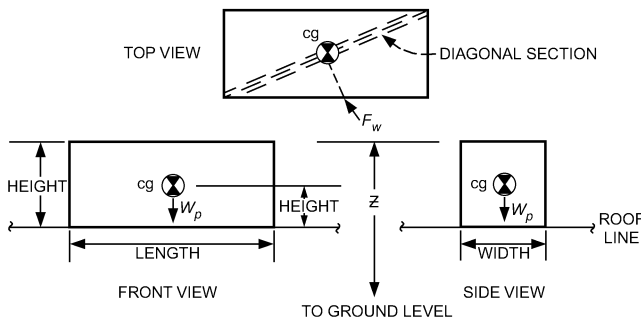
Fig. 12　Equipment Dimensions and Force Locations for Wind Examples 7, 8, and 9

Table 16　Definition of Exposure Categories

Exposure A. Large city centers with at least 50% of the buildings having a height in excess of 70 ft. Use of this exposure category is limited to those areas for which terrain representative of Exposure A prevails upwind for at least 0.5 mile or 10 times the height of the building or structure, whichever is greater.

Possible channeling effects or increased velocity pressures caused by building or structure location in the wake of adjacent buildings needs to be considered.

Exposure B. Urban and suburban areas, wooded areas, or other terrain with numerous closely spaced obstructions the size of single-family dwellings or larger. Use of this exposure category is limited to those areas for which terrain representative of Exposure B prevails upwind for at least 1500 ft or 10 times the height of the building or structure, whichever is greater.

Exposure C. Open terrain with scattered obstructions having heights generally less than 30 ft. This category includes flat open country and grasslands.

Exposure D. Flat, unobstructed areas exposed to wind flowing over open water for a distance of at least 1 mile. This exposure applies only to those buildings and other structures exposed to the wind coming from over the water. Exposure D extends inland from the shoreline for 1500 ft or 10 times the height of the building or structure, whichever is greater.

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Notes:
1. HVAC components for buildings with mean roof height of 60 ft or less are designed on the basis of Exposure C.
2. HVAC components on buildings with mean roof height greater than 60 ft and other structures are designed on basis of exposure categories defined in this table, except assume Exposure B for buildings and other structures sited in terrain representative of Exposure A.

Table 17　Wind Importance Factor *I* (Wind Loads)

Category	*I*
I	0.87
II	1
III	1.15
IV	1.15

Table 18　Exposure Category Constants

Exposure Category	α	Z_g, ft	Gust Factor *G*
A	5	1500	0.8
B	7	1200	0.8
C	9.5	900	0.85
D	11.5	700	0.85

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Note: See Table 17 for definitions of Exposure Categories.

Table 19　Force Coefficients for HVAC Components, Tanks, and Similar Structures

Shape	Type of Surface	C_f for h/D Values of		
		1	7	25
Square (wind normal to face)	All	1.3	1.4	2.0
Square (wind along diagonal)	All	1.0	1.1	1.5
Hexagonal or octagonal $(D\sqrt{Q_z} > 2.5)$	All	1.0	1.2	1.4
Round $(D\sqrt{Q_z} > 2.5)$	Moderately smooth	0.5	0.6	0.7
	Rough $(D'/D = 0.02)$	0.7	0.8	0.9
	Very rough $(D'/D = 0.08)$	0.8	1.0	1.2
Round $(D\sqrt{Q_z} \pounds 2.5)$	All	0.7	0.8	1.2

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Notes:
1. Design wind force calculated based on area of structure projected on a plane normal to the wind direction. Force is assumed to act parallel to wind direction.
2. Linear interpolation may be used for h/D values other than shown.
3. Nomenclature:
　D　= diameter or least horizontal dimension, ft
　D'　= depth of protruding elements such as ribs and spoilers, ft
　h　= structure height, ft
　Q_z　= velocity pressure evaluated at height z above ground level, lb/ft^2

Example 7. Suburban hospital in Omaha, Nebraska. The top of the cooling tower is 100 ft above ground level.

　Solution:

　　From Figure 11, the design wind speed is found to be 90 mph.
　　From Table 16, use Category IV
　　From Table 17, use Exposure A
　　From Table 18, $I = 1.15$
　　From Table 21, $K_z = 0.68$
　　From Table 20, G = 0.8
　Substitution into Equation (65) yields:

$$Q_z = 0.00256 \times 0.68 \times (90)^2 \times 1.15 = 16.22 \text{ lb/ft}^2$$

　Substitution into Equation (64) yields the design wind force as

$$F_w = 16.22 \times 0.8 \times 1.0 \times 224 = 2906 \text{ lb}$$

Example 8. Office building in New York City. Top of tower is 600 ft above ground level.

　Solution:

　　From Figure 11, the design wind speed is 120 mph.
　　From Table 16, use Category II.
　　From Table 17, use Exposure A
　　From Table 18, $I = 1.0$
　　Because $z > 500$ ft, K_z must be determined from Note 2 of Table 21.
　　From Table 20, α = 5.0, $z_g = 1500$, and G = 0.8
　Substituting into the first equation in Note 2 yields

$$K_z = 2.10 \ (Z/Z_g)^{2/\alpha} = 1.39$$

　Substituting into Equation (65) yields

$$Q_z = 0.00256 \times 1.39 \times (120)^2 \times 1.15 = 51.2 \text{ lb/ft}^2$$

　Substituting into Equation (64) yields the design force wind as

$$F_W = 51.2 \times 0.8 \times 1.0 \times 224 = 9175 \text{ lb}$$

Example 9. Church in Key West, Florida. The top of the tower is 50 ft above ground level.

　Solution:

　　From Figure 11, the design speed is found to be 150 mph

Table 20   Classification of Buildings and Other Structures for Wind Loads

Nature of Occupancy	Category
Buildings and other structures that represent a low hazard to human life in event of failure, including, but not limited to, agricultural facilities, certain temporary facilities, and minor storage facilities	I
All buildings and other structures except those listed in Categories I, III, and IV	II
Buildings and other structures that represent a substantial hazard to human life in event of failure, including, but not limited to, - Buildings and other structures where more than 300 people congregate in one area. - Buildings and other structures with elementary and secondary schools, day care facilities with capacity greater than 250 - Buildings and other structures with capacity greater than 500 for colleges or adult education facilities - Health care facilities with capacity of 50 or more resident patients, but not having surgery or emergency treatment facilities - Jails and detention centers - Power generating stations and other public utility facilities not included in Category IV - Buildings and others structures containing sufficient quantities of toxic or explosive substances to be dangerous to the public if released	III
Buildings and other structures designated as essential facilities including, but not limited to, - Hospitals and other health care facilities with surgery and emergency treatment facilities - Fire, rescue, and police stations and emergency vehicle garages - Designated earthquake, hurricane, or other emergency shelters - Communication center and other facilities required for emergency response - Power generating stations and other public utility facilities required in an emergency - Buildings and other structures with critical national defense functions	IV

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From Table 16, use Category III

From Table 17, use Exposure D

From Table 18, $I = 1.15$

From Table 20, G = 0.85

From Table 21, $K_z = 1.27$

From Equation (65):

$$Q_z = 0.00256 \times 1.27 \times 1.15 \times (150)^2 = 84.1 \text{ lb/ft}^2$$

Substituting into Equation (64) gives the design wind force as

$$F_w = 84.1 \times 0.85 \times 1.15 \times 224 = 18{,}415 \text{ lb}$$

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Table 21   Velocity Pressure Exposure Coefficient K_z

Height above ground level z, ft	Exposure A	B	C	D
0 to 15	0.32	0.57	0.85	1.03
20	0.36	0.62	0.90	1.08
25	0.39	0.66	0.94	1.12
30	0.42	0.70	0.98	1.16
40	0.47	0.76	1.04	1.22
50	0.52	0.81	1.09	1.27
60	0.55	0.85	1.13	1.31
70	0.59	0.89	1.17	1.34
80	0.62	0.93	1.21	1.38
90	0.68	0.96	1.24	1.40
100	0.68	0.99	1.26	1.43
120	0.73	1.04	1.31	1.48
140	0.78	1.09	1.36	1.52
160	0.82	1.13	1.39	1.55
180	0.86	1.17	1.43	1.58
200	0.90	1.20	1.46	1.61
250	0.98	1.28	1.53	1.68
300	1.05	1.35	1.59	1.73
350	1.12	1.41	1.64	1.78
400	1.18	1.47	1.69	1.82
450	1.24	1.52	1.73	1.86
500	1.29	1.56	1.77	1.89

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Notes:
1. Linear interpolation for intermediate values of height z is acceptable.
2. For values of height z greater than 500 ft, K_Z must be calculated using the following equations:

$$K_Z = 2.01(z/z_g)^{2/\alpha} \quad \text{For } 15 \text{ ft} \leq z \leq z_g$$

or

$$K_Z = 2.01(15/z_g)^{2/\alpha} \quad \text{For } z < 15 \text{ ft}$$

3. Exposure categories are defined in Table 14.
4. Values for alpha (α) and z_g are found in Table 17.

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CHAPTER 55

ELECTRICAL CONSIDERATIONS

PRODUCTION, delivery, and use of electricity involves countless decisions made along the way, by hundreds of people and companies. This chapter focuses on the decisions to be made about the building and equipment. Creating a building that works means including the best designs available, communicating needs and capabilities, and planning ahead.

For an owner-occupied building, the benefits of a properly designed building return to the owner throughout the building's life. For tenant-occupied spaces, good design means fewer problems with tenant and building system interference (e.g., lighting or appliances in one suite disrupting computers in a neighboring suite).

Because HVAC&R equipment can have a large effect on buildings, it is necessary to address electrical issues in buildings that specifically are caused by or have an effect on HVAC&R equipment.

TERMINOLOGY

Volt (V): practical unit of electric pressure; the pressure that will produce a current of 1 A against a resistance of 1 Ω; equal to 1 J/s. Also called the **electromotive force (emf)**.

Current (I): movement of electrons through a conductor; measured in amperes.

Ampere (A): practical unit of electric current flow. If a 1 Ω resistance is connected to a 1 V source, 1 A will flow.

Alternating current (ac): a current that reverses at regular, recurring intervals of time and that has alternately positive and negative values. The values vary over time in a sinusoidal manner.

Watt (W): unit of real electrical power, equal to the power developed in a circuit by a current of 1 A flowing through a potential difference of 1 V.

Volt-ampere (VA): amount of apparent power in an alternating current circuit equal to a current of 1 A at an emf of 1 V. It is dimensionally equivalent to watts. Volt-ampere is equal to watts when voltage and current are in phase.

Volt-ampere-reactive (VAR): unit for reactive power. The symbols Q and sometimes N are used for the quantity measured in VARs. VARs represent the power consumed by a reactive load (i.e., when there is a phase difference between applied voltage and current).

Power factor: for an ac electric power system, the ratio of the real power to the apparent power, or W/VA.

Three-phase power: supplied by three conductors, with the currents (or voltages) of any two 120° out of phase with each other.

Y (or "wye") connection: a configuration of wiring so that each winding of a polyphase transformer (or three single-phase transformers) is connected to a common point, the "neutral."

Delta-connected circuit: a three-phase circuit that is mesh-connected, so the windings of each phase of a three-phase transformer are connected in a series for a closed circuit (i.e., in a triangle or "delta" configuration).

The preparation of this chapter is assigned to TC 1.9, Electrical Systems.
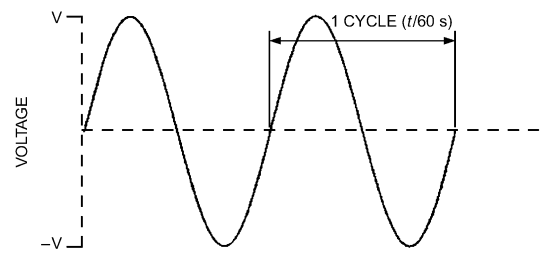
Fig. 1   Fundamental Voltage Wave

Fundamental voltage: produced by an electric ac generator and has a sinusoidal waveform with a frequency of 60 cycles per second, or 60 Hz (in the United States). Other countries may have a similar waveform but at 50 cycles per second of 50 Hz.

Cycle: the part of the fundamental waveform where the electrical potential goes from zero to a maximum to zero to a minimum, and back to zero again (i.e., one complete wave; see Figure 1). At 60 Hz, there are 60 cycles in 1 second.

RMS (root-mean-squared) voltage: an effective way to compare ac to dc value. For a pure sinusoidal waveform, RMS value is equal to 0.707 times the peak magnitude.

System voltage: the RMS phase-to-phase voltage of a portion of an ac electric utility system. Each system voltage pertains to a part of the system bounded by transformers or end-use equipment.

Service voltage: the voltage at the point where the electric systems of the supplier and the user are connected.

Utilization voltage: the voltage at the terminals of the utilization equipment.

Nominal system voltage: the rated system voltage level (i.e., 480 volts) at which the electrical system normally operates. To allow for operating contingencies, utility systems generally operate at voltage levels within –5% to +5% of nominal system voltage.

SAFETY

The greatest danger from electricity is that it is taken for granted and not taken seriously as a hazardous energy source. Electricity can produce bodily harm and property damage, and shut down entire operations. The type of damage from electricity ranges from a mild shock to the body to a major electrical fire. Electrical safety is important in all occupational settings. See information on safety codes in the Electrical Codes section.

PERFORMANCE

In the United States, the National Electrical Code® (NEC) is generally accepted as the minimum safety requirements for wiring and grounding in a structure. Other countries have similar requirements. The NEC ensures building design is safe, but may not provide the performance that a modern building requires. Rapid

55.1

changes in electronic technologies have rendered many traditional electrical distribution practices obsolete and must be replaced with new designs. Electrical power distribution decisions made during design affect occupants' productivity for the life of the building. Many improvements over the minimum requirements are relatively inexpensive to implement as a building is constructed.

Power quality, like quality in other goods and services, is difficult to define. There are standards for voltage and waveshape, but the final measure of power quality is determined by the performance and productivity of equipment used by the building occupant. If the electric power is inadequate for those needs, then the quality is lacking.

Specifications for electric power are set down in recognized national standards. These are voltage levels and tolerances that should be met, on the average, over a long period of time. Electric utilities and building distribution systems generally meet such specifications. Voltage drop in a building is a fundamental reason for calculating the size of electrical conductors. Brief disturbances on the power line are not addressed in these time-averaged specifications; new standards are being developed to address these new concerns.

Interaction between tenants' electrical equipment is an ongoing problem. Often, a large load in one tenant's space can disrupt a small appliance or computer in another part of the building. Voltage drop along building wiring and harmonic distortion are often the causes of the problem. **Dedicated circuits** usually solve the voltage drop problem, but harmonic distortion must be solved at the contributing loads. By eliminating much of the wiring common to both pieces of equipment, the original performance of each is restored. With modern electronic loads, the interaction might easily involve a large load that interferes with smaller, more sensitive equipment. Disturbances might travel greater distances or through nondirect paths, so diagnostics are more difficult.

For tenants of a building with ordinary power distribution, lost productivity associated with power quality problems is an additional operating expense. The disturbance may last only milliseconds, but the disruption to business may require hours of recovery. This multiplication of lost time makes power quality a significant business problem.

Lost productivity may be the time it takes to restart a chiller, to repair a critical piece of equipment, or to retype a document. Another aspect of lost productivity is the stress on employees whose work is lost. The building owner may suffer loss, as well. Certainly the building equipment itself may suffer from the same damage or losses as tenant equipment. Sophisticated energy management systems, security systems, elevator controls, HVAC&R systems, and communications facilities are susceptible to disruption and vulnerable to damage.

ELECTRICAL SYSTEM COMPONENTS AND CONCEPTS

Voltage differential causes electrons to flow. In a direct current (dc) electrical system, electrons flow in only one direction. In an alternating current (ac) electrical system, electrons continually alternate or change direction at a prescribed number of times per second. The main disadvantage of dc voltage is its inability to be boosted or attenuated easily and efficiently. The alternating magnetic fields of ac make boosting or decreasing voltage with transformers feasible, which is why ac has been widely adopted. Electrons flow more efficiently at lower currents because I^2R losses are minimized. For the same load, raising the voltage level reduces the current while delivering the same power. When long distances are involved, electric utility companies step up voltages to very high levels for transmission. However, these voltages are extremely dangerous, so they must be stepped down to a safer, lower, usable voltage before use. Transformers offer an efficient way to change voltage levels (step-up or step-down) for an alternating current power source.

Transformers

Transformers are used to change one voltage to another voltage, typically to step up voltage levels from generators. Power can then be transmitted at a low current (with less loss). At the end of the transmission line, a step-down transformer reduces the voltage to a usable level.

A transformer consists of a ferromagnetic core wrapped with multiple coils, or windings, of wire. The input line is connected to the primary coil, and the output line is connected to the secondary coil. Alternating current I_1 in the primary coil induces an alternating magnetic flux ϕ that flows through the ferromagnetic core, changing direction during each electrical cycle. This flux in turn induces alternating current I_2 in the secondary coil. The voltage V_2 at the secondary coil is directly related to the primary voltage by the turns ratio (i.e., the number of turns N_1 in the primary coil divided by the number turns N_2 in the secondary coil).

An **ideal transformer** with two windings wrapped around a magnetized core is shown in Figure 2. The ideal model for a transformer assumes I^2R losses, core losses, leakage flux, and core reluctance are insignificant. A practical model includes these losses.

Transformer **losses** can be divided into core (or iron) losses, copper losses, and stray losses. Core losses include hysteresis losses and eddy current losses. All ferromagnetic materials tend to retain some degree of magnetization after exposure to an external magnetic field. This tendency to stay magnetized is called hysteresis, and it takes energy to overcome this opposition to change every time the magnetic field produced by the primary winding changes polarity. Eddy current losses result from induced currents circulating in the magnetic core perpendicular to the flux. Because iron conducts both electricity and magnetic flux, eddy currents are induced in the iron just as in the secondary windings from the alternating magnetic field.

Three identical single-phase, two-winding transformers may be connected to form a **three-phase bank**. The four possible connections are Y-Y, Y-Δ, Δ-Y, and Δ-Δ. The U.S. standard for marking three-phase transformers uses H_1, H_2, and H_3 on the high-voltage terminals and X_1, X_2, and X_3 on the low-voltage terminals; A, B, and C identify phases on the high-voltage side of the transformer, and a, b, and c identify phases on the low-voltage side. Typically, three-phase

ϕ = CONSTANT
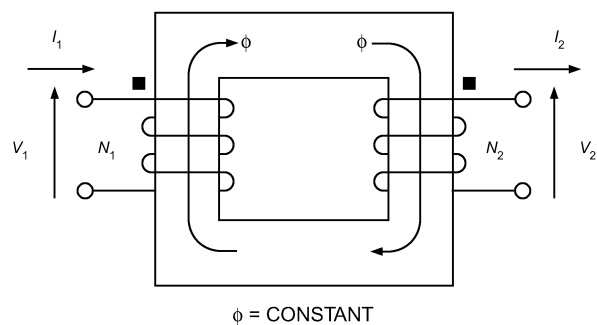
Fig. 2   Ideal Transformer
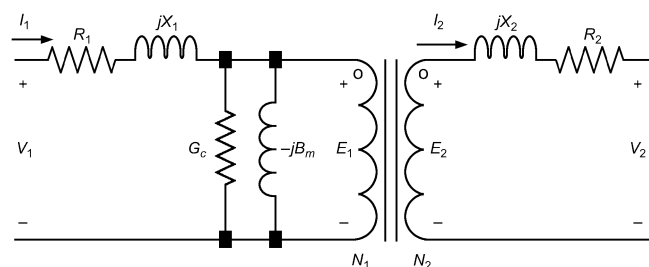
Fig. 3   Transformer Equivalent Circuit

voltages present the higher voltage (phase-to-phase) first, followed by the lower voltage (phase-to-neutral). Single-phase voltages typically present the lower voltage (phase-to-neutral) first, followed by the higher voltage (phase-to-phase). For example, 208/120 V is three-phase and 120/240 V is single-phase.

Y-Y connections (Figure 4) are rarely used because of balancing and harmonics problems.

Y-Δ connections (Figure 5) are typically used for stepping down from high to medium voltage.

The Δ-Y transformer (Figure 6) is commonly used as a generator step-up transformer, where the Δ winding is connected to the generator terminals and the Y winding is connected to the transmission line. One advantage of the high-voltage Y winding is that a neutral point N is provided for grounding on the high-voltage side.

The Δ-Δ transformer (Figure 7) has the advantage that one phase can be removed for repair or maintenance while the remaining phases continue to operate as a three-phase bank. The open Δ connection allows balanced three-phase operation with the kVA rating reduced to 58% of the original bank. These Δ-Δ connections are typically used in distribution networks.

An **autotransformer** has two windings connected in series (Figure 8). Whereas a typical transformer's windings are only coupled magnetically via the mutual core flux, an autotransformer's windings are both electrically and magnetically coupled.

An autotransformer has smaller per-unit leakage impedances than a two-winding transformer; this results in both smaller series voltage drops and higher short-circuit currents. It also has lower per-unit losses, lower excitation current, and lower cost, if the turns ratio

is not large. An autotransformer is not isolated as well as a typical two-winding transformer; transient overvoltages pass through the autotransformer more easily because the windings are connected electrically.

Transformer Coolants and Insulators. Because heat is created by the flow of electrical current through the windings, a liquid (e.g., **oil** or **silicone**) is often used as a coolant inside the transformer. Such liquids are also good electrical insulators for the wire windings and iron core. **Dry transformers** do not require a liquid for cooling, instead using ambient air for cooling as well as insulation. Dust, dirt, moisture, and other contaminants in the air can reduce its insu-
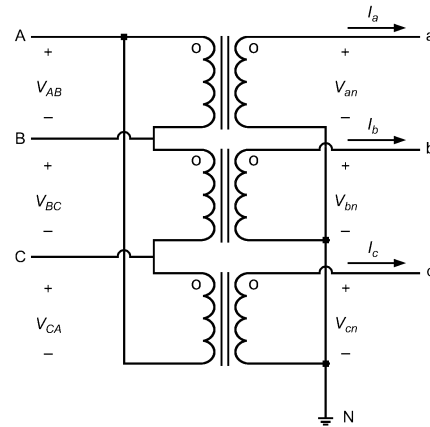
Fig. 6   Three-Phase Δ-Y Transformer
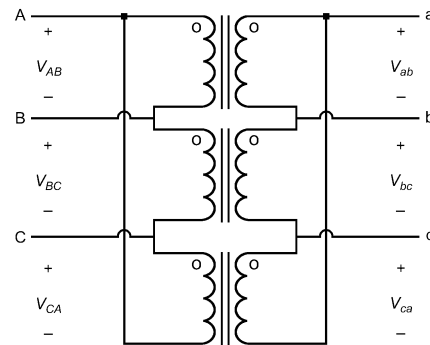
Fig. 7   Three-Phase Δ-Δ Transformer
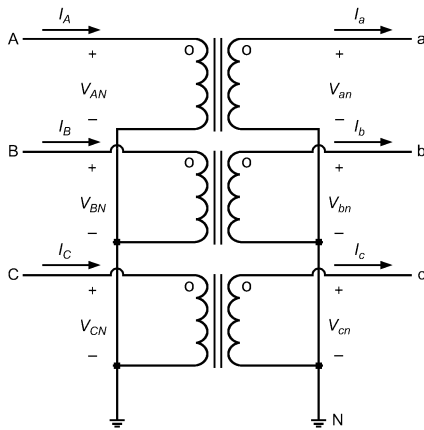
Fig. 4   Three-Phase Y-Y Transformer
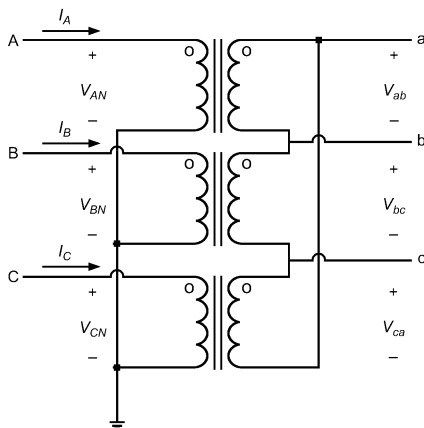
Fig. 5   Three-Phase Y-Δ Transformer
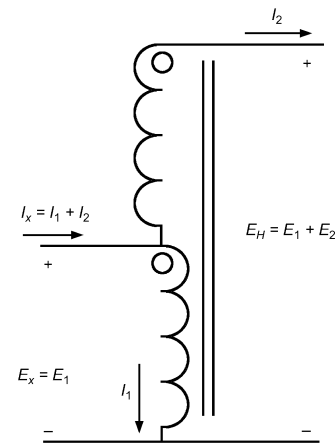
Fig. 8   Typical Autotransformer

lating capabilities and deteriorate exposed parts, and may cause premature failure of the transformer.

Emergency and Standby Power Systems

Emergency Power Supplies. Diesel **generators** are still the dominant source of emergency power, particularly for emergency loads such as fire pumps or elevators, but the constraints of emergency power systems must be understood to ensure proper operation of electrical equipment. This is especially true as standby systems are expanded to carry the full facility load, including HVAC&R systems, and as some diesel engines are replaced with natural gas engines, which have very different acceptable load step characteristics.

Most codes require diesel generators used for life safety loads to be online within 10 s. However, age, battery wear, and even improper exercising of the engine can cause delays and even failures to start. Even if the engine does start within 10 s, some type of ride-through device must support electronic loads (including computers and energy management systems) until the generator has started.

Uninterruptible power supply (UPS) units are most commonly used to keep computers and controls running during the transition. Batteries are sized to meet the load requirement for a specified period of time (usually about 15 min). The UPS provides power through the interruption and, if generators fail to start, provides enough time for orderly system shutdown.

Flywheel technology is gaining ground where larger (e.g., whole-building) loads are supported. The flywheels are also sized for time and load, but may be cost-prohibitive for orderly shutdown and even for engines that do not start until the second or third try (20 to 30 s). It is rare that one is installed to support a natural gas engine that may take between one to three minutes to start.

A key component of the emergency generator system is the automatic transfer switch (ATS) used to switch from the primary source (usually the utility) to the secondary source (usually the generator). The type of switch selected has important ramifications to the overall electrical system. The types of automatic transfer switches are as follows:

Standard ATS (Figure 9)

- *Break-* (from one source) *before-make* (to another source) design.
- Mechanically interlocked electrical contactors move loads from one power source to another.
- Most can optionally be equipped for delayed transition (switch delays in the neutral position for a preset number of seconds). This allows larger (>50 hp) motors' residual voltage to decay before connection to the other source. Other timers are usually available to provide ride-through for one or two recloser operations (used by utilities to keep their system operational during momentary faults caused by falling limbs, high winds, etc.).
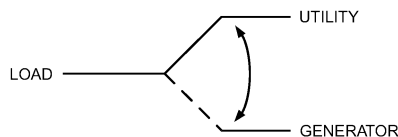
Fig. 9   Break-Before-Make Design for Standard ATS
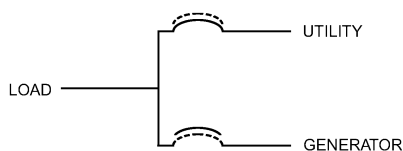
Fig. 10   Closed-Transition ATS

- An *in-phase monitor* can be preset and used in conjunction with or in place of the delayed transition to protect large motors during the transfer process.
- Can be two-, three- or four-pole, depending on phase and grounding scenario.
- Results in at least two momentary power outages: when utility service is lost and when the system switches back to the utility.

Closed-Transition ATS (Figure 10)

- Provides momentary (less than six cycles) connection of load to both power sources within acceptable phase angle for seamless transfer when both sources are available.
- Eliminates the second outage associated with a standard ATS and, in some cases, can be used to operate the generator as a peaking power source.

Bypass-Isolation ATS

- Same as a standard ATS except for its separate bypass mechanism to allow continuation of power to the load from either source while isolating the automatic switch device for maintenance or repair. Typically, the automatic portion of the switch can be mechanically isolated from the frame during this process.
- All other features of the standard ATS apply.
- Closed-transition and bypass-isolation can be combined to provide the capabilities of both.

Service-Entrance-Rated ATS

- Transfer switch includes a circuit breaker or fused device ahead of the transfer mechanism, allowing the device to act as the service-entrance point for building load.
- Fused protection can also be provided ahead of the secondary (generator) entrance point, but is normally omitted in lieu of locating the protection (circuit breaker) at the generator set.
- Can include any or all of the other ATS features listed in standard, closed-transition, or bypass-isolation types.

Parallel-Transfer (PT) Switch (Figure 11)

- Parallel switchgear in a simple one- or two-breaker design allows for parallel connection of the load to both power sources for an indefinite time period.
- Should include all protective relay devices as required by the local utility and generator supplier.
- Can include some of the features of a standard ATS, because most can also be operated as an open-transfer (break-before-make) switch.

Switch selection can profoundly affect the electrical system, especially if an existing back-up system is upgraded for an expanded role. For example, it may be necessary to completely replace the existing switchgear of a building if an original generator system with a small generator and a standard ATS is replaced with a larger generator and a closed-transition ATS.

If the emergency power system is being expanded to include large motor loads, such as chillers, then

- Set delay to account for chiller motor back current to dissipate.
- Size the generator set large enough to handle the motor loads' starting current requirements. The electrical engineer needs to know the starting requirements and maximum allowable voltage drop that the overall electrical system can handle, especially com-
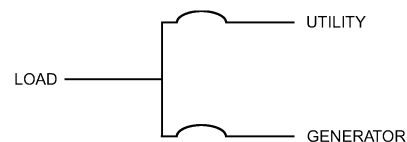
Fig. 11   Parallel-Transfer Switch

puter and control loads. Most major generator manufacturers can provide sizing software.

If a standard ATS is being replaced with a closed-transition or parallel-transfer switch,

- Verify that the existing switchgear can handle the added potential fault current of the generator set. For instance, if the available fault current from the utility is 65,000 A and the generator fault current is 30,000 A, then the system only has to be braced for 65,000 A with a standard ATS. It has to be braced for 95,000 A with either of the other two switches because fault current is additive with multiple sources connected at the same time.

If the emergency power system is being converted from diesel to natural gas, then

- Check the acceptable load steps of the new engine: the diesel likely accepted 100% load, but the natural gas engine may be limited to as low as 20% load. Chillers and other large loads frequently exceed the acceptable load increase.
- Determine whether large-motor-load starting systems can be changed to reduce starting requirements and meet acceptable load steps.

If the emergency system is being modified for peaking or curtailment uses, then

- Obtain the specific utilities interconnection requirements; these tend to be utility-specific and may exceed normal NEC or local codes.
- Check the existing system for closed-transition or parallel-transfer switch issues and compatibility.
- Investigate emissions issues; standby emissions permit requirements are almost always less stringent than peaking requirements.

If the emergency system includes a UPS or flywheel system, then

- Size the UPS or flywheel for the maximum required load for a specific time; remember that capacity of these systems is x kW for y min.
- Avoid motor loads as much as possible.

Motors

Motor Control and Protection. Motor control must be effective without damaging the motor or its associated equipment. Control must be designed to prevent inadvertent motor starting caused by a fault in the control device. The control should be able to sense motor conditions to keep the motor windings from getting too warm.

Motor protection involves sensing motor current and line voltage, and can include bearing vibration, winding temperature, bearing temperature, etc. Motor temperature increase has two basic sources. Heating occurs when dirt or debris blocks airflow over or through the motor, or it comes from the motor current, commonly referred to as I^2R, where I is motor current and R is motor resistance. Because the current is squared, its contribution is exponential. R is the motor winding resistance, and is quite small. Therefore, motor resistance contributes a linear function to heating (and therefore temperature rise) in the motor. Motor windings can withstand temperature rise, depending on the motor winding temperature rating. The second source of motor temperature increase is lack of motor cooling. The primary source of cooling is moving air, usually from a shaft-driven fan. As a motor slows down, the fan runs more slowly; therefore, the less air movement, the less cooling. Because fan loads are also exponential, a small decrease in motor speed greatly reduces airflow on the motor, reducing cooling. To compound the issue, the slower the motor runs, the greater the slip, and the greater the motor current. This then becomes a vicious circle.

Motor Starters and Thermal Overloads. Motor starters start, stop, protect, and control the motor. They sense motor current based

on a time curve: the shorter the time, the more current they let through. They may also limit the number of motor starts in a given period of time so the motor does not exceed its ANSI rating. Another cause for concern is the starter's ambient temperature: if it is different from the ambient temperature around the motor controller, the thermal overloads need to be sized accordingly.

Several motor starter types are available, and they can function several different ways. The **across-the-line** starter is the simplest but may disturb electric service because of high motor-starting current requirements. The **part-winding**, **reduced-voltage**, and **wye-delta** starters all act by reducing the starting voltage on the motor. Fan and pump loads can usually be started this way; this reduces starting current draw and demand, but sacrifices motor starting speed. **Soft-start** starters also reduce the voltage and limit demand during starting, thereby easing stress on the electric system during motor starting. **Variable-frequency drives (VFDs)** are also used to soft-start a motor, and are designed to control acceleration during starting as well as optimize motor speed to its load. See the section Motor-Starting Methods for more information.

A VFD converts ac to dc and then back to variable-frequency, variable-voltage ac. Motor speed is varied by varying the frequency of the ac output voltage, typically using pulse-width modulation (PWM). This power conversion process results in distorted input current and may contribute to building power system voltage distortion. When motors and other loads are supplied from a distorted voltage source, their operating temperatures may rise.

Phase Loss Protection. Phase loss can be detected by sensing either voltage loss or current loss on one of the phases. Motor overloads often are set based on the nameplate data of the motor, but the real motor current draw is less because the motor may not be fully loaded. If one of three phases is lost, the current increases in the other two phases, but not by enough to trip the overloads. However, it will overheat and possibly damage the motor. Some phase loss detectors also check phase current to be sure that it is balanced within 10%. This protects the motor and makes the operator aware of potential motor or line problems.

Motor-Starting Effects. The following effects do not occur with all motors. For instance, brushless dc and inverter-driven motors, which are electronically controlled, do not have inrush currents that cause light dimming or sags.

Light Dimming or Voltage Sags. Light dimming or voltage sag associated with motor starts can be more than a nuisance. Motors have the undesirable effect of drawing several times their full load current while starting. This large current, by flowing through system impedances, may cause voltage sag that can dim lights, cause contactors to drop out, and disrupt sensitive equipment. The situation is worsened by an extremely poor starting displacement factor, usually in the range of 15 to 30%. If the motor-starting-induced voltage sag deepens, the time required for the motor to accelerate to rated speed increases. Excessive sag may prevent the motor from starting successfully. Motor-starting sags can persist for many seconds.

The Illuminating Engineering Society of North America (IESNA) is precise in describing lighting reactions. *Dimming* is an intentional technique to enhance the ambiance of surroundings by varying the perceived lighting levels. It is also used to reduce the electrical power used by lamps when adequate natural lighting is available; the controller electronically follows the natural variations in a way that will not be optically perceived. Similarly, *flicker* is deliberately selected in some lamps to resemble a candle's flame. In contrast, this chapter discusses possible causes of *undesirable, perceptible* reductions of a lamp's lumen output.

Momentary undesirable lighting reduction was quite common when building owners selected incandescent lamps, which compete with motors for available electrical current, to provide the desired lighting levels. More efficient lamps are now the norm for almost every application. For fluorescent lamps, electronic ballasts convert the 60 Hz electrical service to much higher frequencies, which elim-

inates perception of irritating flicker, and provides greater lumens per watt than the former magnetic ballasts. Similar improvements have occurred for mercury, metal halide, and sodium lamps, typically found in large stores, sports, and industrial applications. Including electronic circuitry in the lamps and lighting systems makes power quality even more important for building owners: electronic components are sensitive to both lower and upper threshold voltages, yet the building's voltage may experience momentary voltage sag as large motors are started. Specific product literature for lamps, lamp ballasts, and lighting controls should be reviewed to ensure client satisfaction with operation of the HVAC system's motors and controls.

Motor-Starting Methods. The following motor-starting methods can reduce voltage sag from motor starts.

An **across-the-line start**, energizing the motor in a single step (full-voltage starting), provides low cost and allows the most rapid acceleration. It is the preferred method unless the resulting voltage sag or mechanical stress is excessive.

Autotransformer starters have two autotransformers connected to open delta (similar to a delta connection using three single-phase transformers, but with one transformer removed; carries 57.7% of a full delta load). Taps provide a motor voltage of 80, 65, or 50% of system voltage during start-up. Starting torque varies with the square of the voltage applied to the motor, so the 50% tap delivers only 25% of the full-voltage starting torque. The lowest tap that will supply the required starting torque is selected. Motor current varies as the voltage applied to the motor, but line current varies with the square of the tap used, plus transformer losses of ~3%.

Resistance and **reactance starts** initially insert impedance in series with the motor. After a time delay, this impedance is shorted out. Starting resistors may be shorted out over several steps; starting reactors are shorted out in a single step. Line current and starting torque vary directly with the voltage applied to the motor, so for a given starting voltage, these starters draw more current than the line with autotransformer starts, but provide higher starting torque. Reactors are typically provided with 50, 45, and 37.5% taps.

Part-winding starters are attractive for use with dual-rated motors (220/440 V or 230/460 V). The stator of a dual-rated motor consists of two windings connected in parallel at the lower voltage rating, or in series at the higher voltage rating. When operated with a part-winding starter at the lower voltage rating, only one winding is energized initially, limiting starting current and torque to 50% of the values seen when both windings are energized simultaneously.

Delta-wye starters connect the stator in wye for starting, then after a time delay, reconnect the windings in delta. The wye connection reduces the starting voltage to 57% of the system line-line voltage, starting current and starting torque are reduced to 33% of their values for full voltage start.

Utilization Equipment Voltage Ratings

Utilization equipment is electrical equipment that converts electric power into some other form of energy, such as light, heat, or mechanical motion. Every item of utilization equipment should have a nameplate listing, which includes, among other things, the rated voltage for which the equipment is designed. In some cases the nameplate will also indicate the maximum and minimum voltage for proper operation. With one major exception, most utilization equipment carries a nameplate rating that is the same as the voltage system on which it is to be used: that is, equipment to be used on 120 V systems is rated 120 V. The major exception is motors and equipment containing motors, where performance peaks in the middle of the tolerance range of the equipment: better performance can be obtained over the tolerance range specified in ANSI *Standard* C84.1 by selecting a nameplate rating closer to the middle of this tolerance range. The difference between the nameplate rating of utilization equipment and the system nominal voltage is necessary because the performance guarantee for utilization
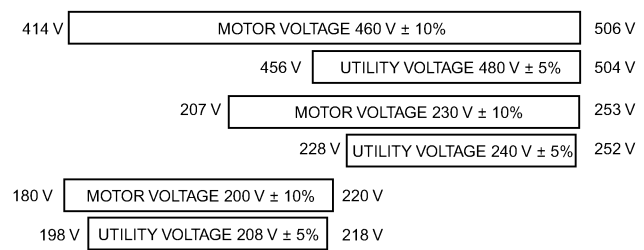
Fig. 12   Utilization Voltages Versus Nameplate Ratings

equipment is based on the nameplate rating and not on the system nominal voltage.

The voltage tolerance limits in ANSI *Standard* C84.1 are based on ANSI/NEMA *Standard* MG 1, Motors and Generators edition, which establishes voltage tolerance limits of the standard low-voltage induction motor at ±10% of nameplate voltage ratings of 230 and 460 V. Because motors represent the major component of utilization equipment, they were given primary consideration in the establishment of this voltage standard. Figure 12 compares utilization voltages to nameplate ratings.

Voltage Level Variation Effects

Whenever voltage at the terminals of utilization equipment varies from its nameplate rating, equipment performance and life expectancy change. The effect may be minor or serious, depending on the equipment characteristics and the amount of voltage deviation from the nameplate rating. NEMA standards provide tolerance limits within which performance will normally be acceptable. In precise operations, however, closer voltage control may be required. In general, a change in the applied voltage causes a proportional change in the current. Because the effect on the load equipment is proportional to the product of the voltage and the current, and because the current is proportional to the voltage, the total effect is approximately proportional to the square of the voltage.

However, the change is only approximately proportional and not exact: the change in the current affects the operation of the equipment, so the current continues to change until a new equilibrium position is established. For example, when the load is a resistance heater, the increase in current increases the heater temperature, which increases its resistance and, in turn, reduces the current. This effect will continue until a new equilibrium current and temperature are established. In the case of an induction motor, a voltage reduction reduces the current flowing to the motor, causing the motor to slow down. This reduces the impedance of the motor, increasing the current until a new equilibrium position is established between the current and motor speed.

Voltage Selection

Generally, the preferred utilization voltage for large commercial buildings is 480Y/277 V, three-phase. The three-phase power load is connected directly to the system at 480 V, and fluorescent ceiling lighting is connected phase-to-neutral at 277 V. Dry-type transformers rated 480 V/208Y/120 V are used to provide 120 V single-phase for convenience outlets and 208 V three-phase for other building equipment. Single-phase transformers with secondary ratings of 120/240 V may also be used to supply lighting and small office equipment. However, single-phase transformers should be connected in sequence on the primary phases to maintain balanced load on all phases of the primary system.

Where the supplying utility furnishes the distribution transformers, the choice of voltages will be limited to those the utility will provide. For tall buildings, space will be required on upper floors for transformer installations and the primary distribution cables supplying the transformers. Apartment buildings generally have the option

of using either 208Y/120 V three-phase/four-wire systems, or 120/240 V single-phase systems, because the major load in residential occupancies consists of 120 V lighting fixtures and appliances. The 208Y/120 V systems are often more economical for large apartment buildings. Single-phase 120/240 V systems should be satisfactory for small apartment buildings and other small buildings.

However, large single-phase appliances, such as electric ranges and water heaters rated for use on 120/240 V single-phase systems, will not perform to the rated wattage on a 208Y/120 V systems, because the line-to-line voltage is appreciably below the rated voltage of the appliance.

POWER QUALITY VARIATIONS

Power quality refers to varied parameters that characterize the voltage and current for a given time and at a given point on the electric system. A power quality problem is usually any variation in the voltage or current that actually results in failure or misoperation of equipment in the facility. Therefore, power quality evaluations are a function of both the power system characteristics and the sensitivity of equipment connected to the power system.

This section defines the different kinds of power quality variations that may affect equipment operation. Important reasons for categorizing power anomalies include the following:

- Identifying the cause of the power anomalies. Understanding the characteristics of a power quality variation can often help identify the cause.
- Identifying the possible effects on equipment operation. A transient voltage can cause failure of equipment insulation; a sag in voltage may result in dropout of sensitive controls based on an undervoltage setting.
- Determining the requirements for measurement. Some power quality variations can be characterized with simple voltmeters, ammeters, or strip chart recorders. Other conditions require special-purpose disturbance monitors or harmonic analyzers.
- Identifying methods to improve the power quality. Solutions depend on the type of power quality variation. Transient disturbances can be controlled with surge arrestors, whereas momentary interruptions could require an uninterruptible power supply (UPS) system for equipment protection. Harmonic distortion may require special-purpose harmonic filters.

Power quality can be described in terms of *disturbances* and *steady-state variations*.

Disturbances. Disturbances are one-time, momentary events. Measurement equipment can characterize these events by using thresholds and triggering when disturbance characteristics exceed specified thresholds. Examples include transients, voltage sags and swells, and interruptions.

Steady-State Variations. Changes in the long-term or steady-state conditions can also result in equipment misoperation. High harmonic distortion levels can cause equipment heating and failure, as can long-term overvoltages or unbalanced voltages. These are variations best characterized by monitoring over a longer period of time with periodic sampling of the voltages and currents. Steady-state variations are best analyzed by plotting trends of the important quantities (e.g., RMS voltages, currents, distortion levels).

These two types of power quality are further defined in seven major categories and numerous subcategories. There are three primary attributes used to differentiate among subcategories within a power quality category: frequency components, magnitude, and duration. These attributes are not equally applicable to all categories. For instance, it is difficult to assign a time duration to a voltage flicker, and it is not useful to assign a spectral frequency content to variations in the fundamental frequency magnitude (sags, swells, overvoltages, undervoltages, interruptions).

Each category is defined by its most important attributes for that particular power quality condition. These attributes are useful for evaluating measurement equipment requirements, system characteristics affecting power quality variations, and possible measures to correct problems. The terminology has been selected to agree as much as possible with existing terminology used in technical papers and standards.

The following descriptions focus on causes of the power quality variations, important parameters describing the variation, and effects on equipment.

Transients

Transients are probably the most common disturbance on distribution systems in buildings and can be the most damaging. Transients can be classified as impulsive or oscillatory. These terms reflect the waveshape of a current or voltage transient.

Impulsive Transient. An impulsive transient (spikes or notches) is considered unidirectional; that is, the transient voltage or current wave is primarily of a single polarity (Figures 13 and 14). Impulsive transients are often characterized simply by magnitude and duration. Another important component that strongly influences the effect on many types of electronic equipment is the **rate of rise**, or rise time of the impulse. This rate of rise can be quite steep, and can be as fast as several nanoseconds. Repetitive subtractive transients (Figure 14), often caused by thyristors such as silicon controlled rectifiers (SCRs), are referred to as voltage notches.

The high-frequency components and high rate of rise are important considerations for monitoring impulses. Very fast sampling rates are required to characterize impulses with actual waveforms. In many power quality monitors, simple circuits are used to detect the transient's peak magnitude and duration (or volt-seconds). If impulse waveshapes are recorded, they usually do not include the fundamental frequency (60 Hz) component. When evaluating these disturbances, it is important to remember that stress on equipment is based on the impulse magnitude plus the magnitude of the fundamental component at the instant of the impulse. The voltage, current available, and pulse width determine the amount of energy available in a transient.

Oscillatory Transient. An oscillatory transient (Figure 15) is a voltage or current that changes polarity rapidly. Because the term "rapidly" is nebulous, the frequency content is used to divide
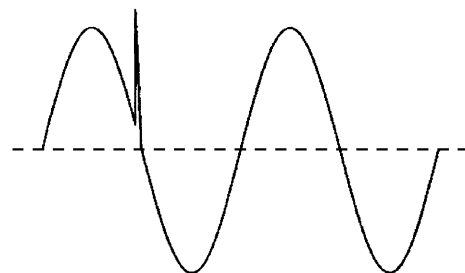
Fig. 13   Example of Spike
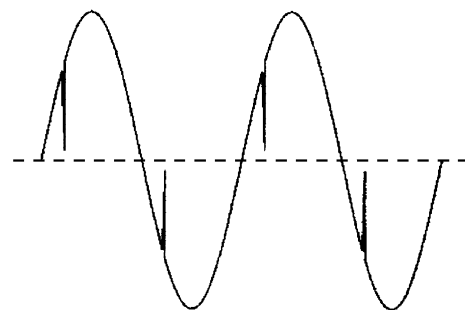
Fig. 14   Example of Notch
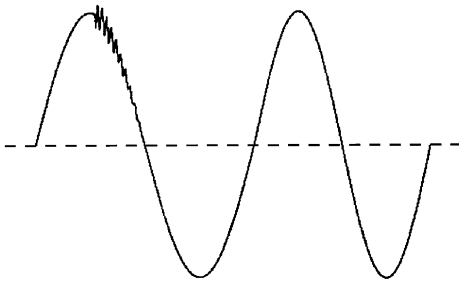
Fig. 15 Example of Oscillatory Transient

Fig. 16 Example of Sag

oscillatory transients into three subcategories: high, medium, and low frequency. Frequency ranges from these classifications are chosen to coincide with common types of power system oscillatory transient phenomena.

As with impulsive transients, oscillatory transients can be measured with or without including the fundamental frequency. One way to trigger on transients is to continually test for deviation in the waveform from one cycle to the next. This method will record any deviation exceeding the set threshold. When characterizing the transient, it is important to indicate the magnitude with and without the 60 Hz fundamental component.

Transients are generally caused by a switching event or by the response of the system to a lightning strike or fault. The oscillations result from interactions between system capacitances and inductances, and occur at the natural frequencies of the system excited by the switching event or fault.

High-frequency transients can occur at locations very close to the initiating switching event. Rise times created by closing a switch can be as fast as a few tens of nanoseconds. Short lengths of circuit have very high natural oscillation frequencies that can be excited by a step change in system conditions (e.g., operating a switch). Power electronic devices such as transistors and thyristors/SCRs can cause high-frequency transients many times during each cycle of the fundamental frequency. The transients can be in the tens or hundreds of kilohertz, and occasionally higher.

Because of the high frequencies involved, circuit resistance typically damps transients out; thus, they only occur close (within hundreds of feet) to the site of the switching event that generates them. Characterizing these transients with measurements is often difficult because high sampling rates are required.

Medium-frequency transients are associated with switching events with somewhat longer circuit lengths (resulting in lower natural frequencies). Switching events on most 480 V distribution systems in a facility cause transient oscillations within this frequency range, which can propagate over a significant portion of the low-voltage system. Motor interruption (definite interruption) is a good example of a common switching event that can excite transients in this frequency range.

Transients coupled from the primary power system (e.g., coupled through the step down transformer) can also cause medium-frequency transients. The most common cause of transients on the primary power system is capacitor switching.

Capacitor energizing results in an initial step change in the voltage, which gets coupled through stepdown transformers by the transformer capacitance and then excites natural frequencies of the low-voltage system (typically 2 to 10 kHz). **Low-frequency transients** are usually caused by capacitor switching, either on the primary distribution system or within the customer facility. Lower-frequency transients result from capacitance of the switched capacitor bank oscillating with the inductance of the power system. The natural frequencies excited by these switching operations are much lower than those of the low-voltage system without the capacitor bank, because of the large capacitance of the capacitor bank itself.
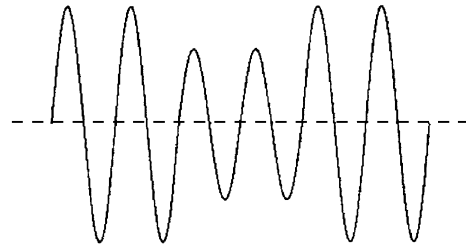
Capacitor switching operations are common on most distribution systems and many transmission systems. Energizing a capacitor results in an oscillatory transient with a natural frequency in the range of 300 to 2000 Hz (depending on the capacitor size and the system inductance). The peak magnitude of the transient can approach twice the normal peak voltage (per unit), and lasts between 0.5 and 3 cycles, depending on system damping.

Isolation transformers, voltage arresters, and/or filters can reduce transients.

Short-Duration Variations

Short-duration voltage variations are momentary changes in the fundamental voltage magnitude. Common causes are faults on the power system (short circuits between phases or from phase to ground). Depending on the fault location and system conditions, the fault can cause either momentary voltage rises (swells) or momentary voltage drops (sags). The fault condition can be close to or remote from the point of interest.

Sags. Sags (Figure 16) are often associated with system faults but can also be caused by switching heavy loads or starting large motors (usually a longer-duration variation). Figure 16 shows a typical voltage sag that can be associated with a remote fault condition. For instance, a fault on a parallel feeder circuit (on the primary distribution system) results in a voltage drop at the substation bus that affects all of the other feeders until the fault is cleared by opening a fuse or circuit breaker.

The percent drop in the RMS voltage magnitude and duration of the low-voltage condition are used to characterize sags. Voltage sags are influenced by system characteristics, system protection practices, fault location, and system grounding. The most common problem caused by voltage sags is tripping sensitive controls (e.g., adjustable-speed drives or process controllers), relays or contactors dropping out, and failure of power supplies to ride through the sag. Many types of voltage regulators are not fast enough to provide voltage support during sags, but ferroresonant transformers and some other line conditioners can provide some ride-through capability or can quickly compensate for deep sags.

In practice, sags are the type of power quality variation that most frequently causes problems. Fault conditions remote from a particular customer can still cause voltage sags that can cause equipment problems. Because there are no easy ways to eliminate faults on the power system, it is always necessary for customers to consider the effects of sags.

Swells. Swells or **surges** can also be associated with faults on the primary distribution system (Figure 17). They can occur on non-faulted phases when there is a single-line-to-ground fault.

Swells are characterized by their magnitude (RMS value) and duration. The severity of a voltage swell is a function of fault location, system impedance, and grounding. On a three-phase ungrounded system (delta), the line-to-ground voltages on the ground phases are 1.73 per unit (i.e., 1.73 times the normal line-to-ground voltage) during a single-line-to-ground fault condition. Close to the substation on a grounded system, there is no voltage rise on the ground phases because the substation transformer is usually delta-wye, providing a low-impedance path for the fault current.
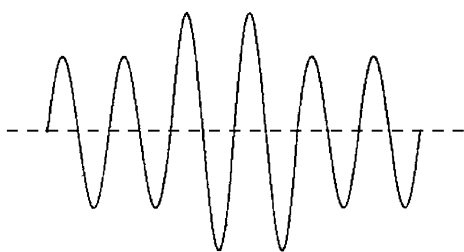
Fig. 17   Example of Swell (Surge)
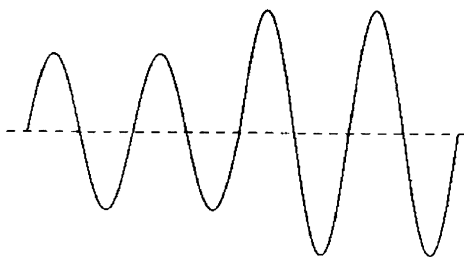
Fig. 18   Example of Overvoltage
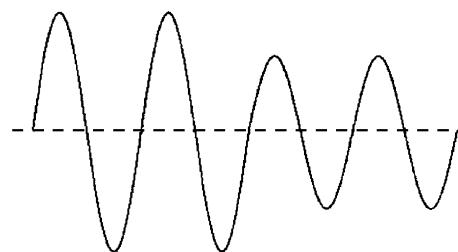
Fig. 19   Example of Undervoltage
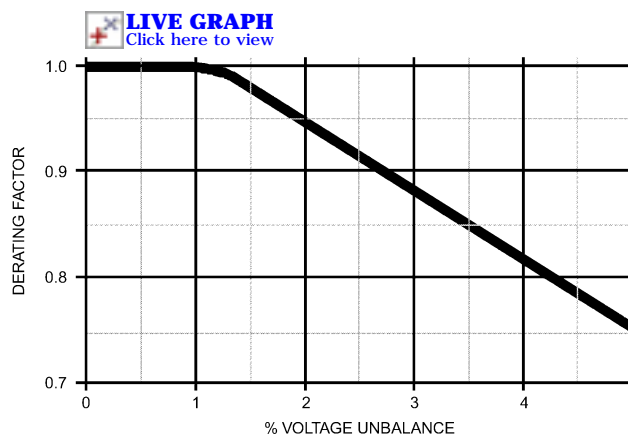
Fig. 20   Derating Factor Curve

Long-Duration Variations

Long-duration RMS voltage deviations generally do not result from system faults. They are caused by load changes on the system and system switching operations. The duration of these voltage variations depends on the operation of voltage regulators and other types of voltage control on the power system (e.g., capacitor controls, generator exciter controls). The time required for these voltage controllers to respond to system changes ranges from large fractions of a second to seconds. Long-duration variations can be overvoltages or undervoltages, depending on the cause of the variation. Voltage unbalance should be considered when evaluating steady-state or long-duration voltage variations. Unbalanced voltages can be one of the major causes of motor overheating and failure. With increasing emphasis on energy-efficient motors, requirements for voltage balance (i.e., limitations on negative sequence voltage magnitudes) may become even more important.

Overvoltages. Overvoltages (Figure 18) can result from load switching (e.g., switching off a large load), variations in system generation, or variations in reactive compensation on the system (e.g., switching a capacitor bank on). These voltages must be evaluated against the long-duration voltage capability of loads and equipment on the system. For instance, most equipment on the power system is only rated to withstand a voltage 10% above nominal for any length of time. Many sensitive loads can have even more stringent voltage requirements.

Long-duration overvoltages must also be evaluated with respect to the long-time overvoltage capability of surge arresters. Metal oxide variation (MOV) arresters in particular can overheat and fail due to high voltages for long durations (e.g., seconds).

Overvoltages can be controlled with voltage regulation equipment either on the power system or in a customer's facility. This can include various tap-changing regulators, ferroresonant regulators, line power conditioners, motor-generator sets, and uninterruptible power supplies.

Undervoltages. Undervoltages (Figure 19) have the opposite causes of overvoltages. Adding a load or removing a capacitor bank will cause an undervoltage until voltage regulation equipment on the system can bring the voltage back to within tolerances.

Motor starting is one of the most common causes of undervoltages. An induction motor draws 6 to 10 times its full load current during starting. This lagging current causes voltage drops in the system impedance. If the started motor is large enough relative to the system strength, these voltage drops can result in a significant system undervoltage. The magnitude of this starting current decreases over a period ranging from 1 s to minutes, depending on the inertia of the motor and the load, until the motor reaches full speed. This type of undervoltage can be mitigated by using various starting techniques to limit the starting current and is largely self-corrected when the starting is completed. For more information, see the section on Motor-Starting Effects.

Voltage Unbalance. Ideally, all phase-to-phase voltages to a three-phase motor should be equal or balanced. Unbalance between the individual phase voltages is caused by unbalanced loading on the system and by unbalances in the system impedances. Voltage unbalance is an important parameter for customers with motors because most three-phase motors have fairly stringent limitations on negative-sequence voltage (a measure of voltage unbalance), which is generated in the motor by unbalances in supplied voltages. Negative sequence currents heat the motor significantly. Voltage unbalance limitations (and steady-state voltage requirements in general) are discussed in ANSI *Standard* C84.1. The National Electrical Manufacturers Association (NEMA) has developed standards and methods for evaluating and calculating voltage unbalance. Unbalance, as defined by NEMA, is calculated by the following equation:

$$\% \text{ Voltage unbalance } = 100 \times \frac{\text{Maximum deviation from average voltage}}{\text{Average voltage}}$$

The motor derating factor caused by the unbalanced voltage curve from NEMA *Standard* MG 1 shows the nonlinear relationship between the percent of voltage unbalance and the associated derating factor for motors (Figure 20). A balanced-voltage three-phase power supply to the motor is essential for efficient system operation. For example, a voltage unbalance of 3.5% can increase motor losses by approximately 15%.

Interruptions and Outages

Interruptions can result from power system faults, equipment failures, generation shortages, control malfunctions, or scheduled maintenance. They are measured by their duration (because the voltage magnitude is always zero), which is affected by utility protection system design and the particular event causing the interruption.

Interruptions of any significant duration can potentially cause problems with a wide variety of different loads. Computers, controllers, relays, motors, and many other loads are sensitive to interruptions. The only protection for these loads during an interruption is a back-up power supply, a back-up generator (requires time to get started) or a UPS system (can constantly be online).

Momentary Interruption. A typical momentary interruption (Figure 21) lasts less than 3 s and occurs during a temporary fault, when a circuit breaker successfully recloses after the fault has been cleared. Lightning-induced faults usually fall into this category unless they cause a piece of equipment (e.g., transformer) to fail.

Temporary Interruption. Temporary interruptions that last between 3 s and 1 min result from faults that require multiple recloser operations to clear, or require time for back-up switching to reenergize portions of the interrupted circuit (e.g., automatic throwover switches).

Power Failure/Blackout. Outages lasting at least 1 min (Figure 22) are severe enough to be included in utility companies' reliability statistics. These failures are caused by fault conditions, maintenance operations that require repair crews, and emergency situations called blackouts.

Solutions involve using either UPS systems or back-up generators, depending on the critical nature of the load. UPS systems typically can provide uninterrupted supply for at least 15 min (based on battery capacity). This covers all momentary and temporary interruptions and provides sufficient time for an orderly shutdown. A UPS can be used in conjunction with a switching scheme involving multiple feeds from the utility to provide an even higher level of reliability. If back-up power is required beyond the capability of a UPS system, and multiple feeds are not realistic or adequate, then back-up generators are needed. On-site generators are typically used in these applications.
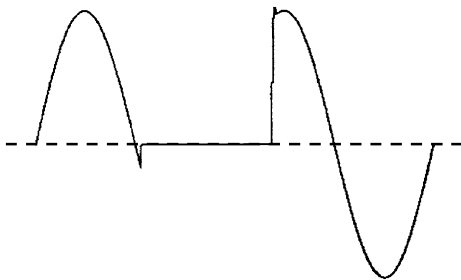
Fig. 21 Example of Momentary Interruption

SUSTAINED INTERRUPTION
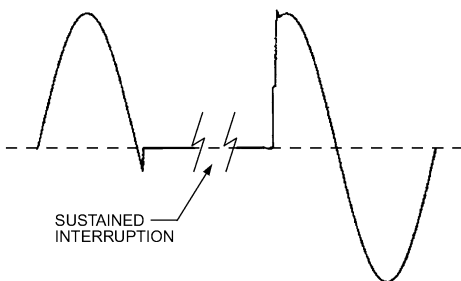
Fig. 22 Example of Blackout or Power Failure Waveform

Brownout. A brownout is a long-term voltage reduction, usually of 3 to 5%. This is an intentional reduction to reduce load under emergency system conditions.

Harmonic Distortion

Harmonic distortion of the voltage waveform occurs because of the nonlinear characteristics of devices and loads on the power system. These nonlinear devices fall into one of three categories:

- Power electronics
- Ferromagnetic devices (e.g., transformers)
- Arcing devices

These devices usually generate harmonic currents, and voltage distortion on the system results from these harmonics interacting with the system impedance characteristics. Harmonic distortion is a growing concern for many customers and for the overall power system because of the increasing applications of power electronic equipment. In many commercial buildings, electronic loads, such as variable-frequency drives, computers, and UPS systems, may be dominant in the facility. With more and more buildings switching to electronic ballasts for fluorescent lighting, an even higher percentage of the facility load falls into this category.

Harmonic distortion levels can be characterized by the complete harmonic spectrum with magnitudes and phase angles of each individual harmonic component. However, it is more common to use a single quantity, the **total harmonic distortion (THD)**, to characterize harmonic distortion of a particular waveform. It is important in general to distinguish between voltage distortion and current distortion because these quantities are handled differently in the standards and should be handled differently when performing measurements and interpreting data.

Voltage and current distortion is caused by the harmonic currents generated by nonlinear devices interacting with the impedance characteristics of the power system. Harmonic current distortion results in elevated true RMS current, which increases I^2R losses and elevated peak current. Because harmonics flow at frequencies higher than the fundamental frequency (e.g., 180 Hz, 300 Hz, 420 Hz), additional losses are experienced because of the reduction of conductor effective cross-sectional area, a phenomenon known as **skin effect**. These losses are attributed to I^2X_L at each harmonic frequency.

A particular concern is when resonance conditions on the power system magnify harmonic currents and high-voltage distortion levels. The natural resonance of the power system varies based on system inductance and capacitance and should be evaluated when adding nonlinear devices (equipment) or power factor capacitors to the system. Capacitors offer a low-impedance path to harmonic frequencies and can therefore attract harmonics, often resulting in reduced life, fuse blowing, or capacitor failure. Figure 23 illustrates the voltage waveform with harmonic content. Figures 24 and 25 illustrate distorted current waveforms.

Harmonic distortion can be reduced by adding an ac line reactor or harmonic filter at the input of individual nonlinear loads (Figure 26). A 5% impedance line reactor typically reduces
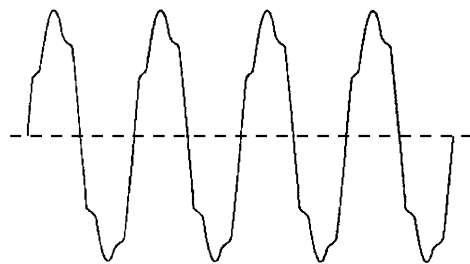
Fig. 23 Example of Harmonic Voltage Distortion

harmonic distortion for three-phase nonlinear loads to about 35% of the fundamental current.

Harmonic current distortion can be reduced to levels of 5 to 8% total harmonic current distortion, at the individual load, using a typical low-pass harmonic filter (Figure 27). The benefit of reducing harmonics right at the contributing load is that the entire upstream power system benefits from reduced levels of current and voltage distortion.

Voltage Notches. A voltage waveform with notches (see Figure 14) caused by operating power electronics, especially where SCRs are involved [e.g., adjustable-speed drives (ASDs)], can be considered a special case that falls in between transients and harmonic distortion. Because notching occurs continuously (steady state), it can be characterized by the harmonic spectrum of the affected voltage. However, frequency components associated with the notching

A. THREE-PHASE INPUT WAVEFORM   B. SPECTRUM
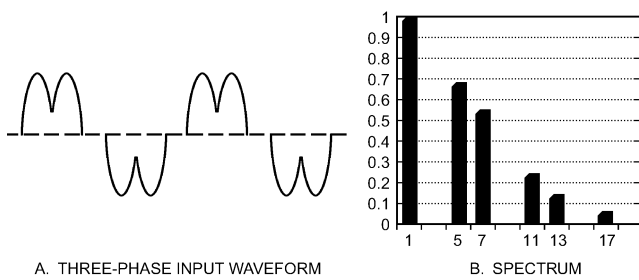
Fig. 24   Example of Harmonic Current Distortion for Six-Pulse Rectifier with 5% Impedance Reactor
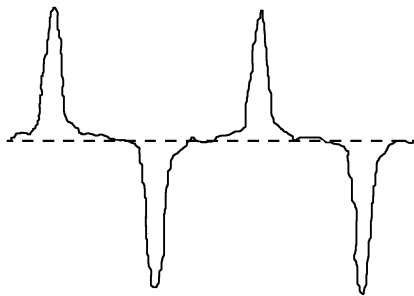
Fig. 25   Example of Harmonic Current Distortion for One-Phase Input Current for Single Personal Computer

INPUT CURRENT WAVEFORM
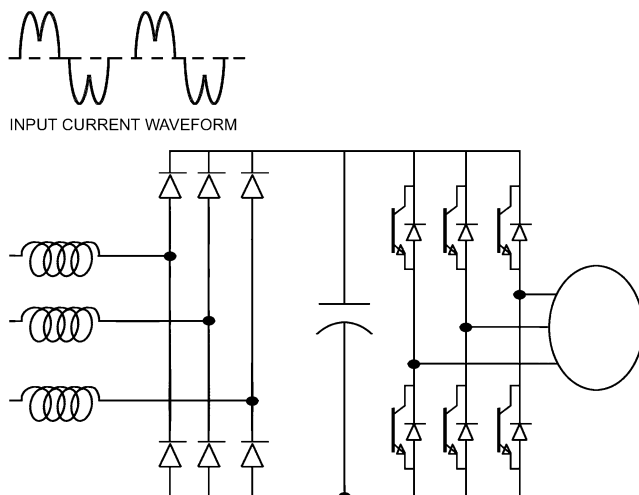
Fig. 26   Example of VFD with ac Line Reactor

can be quite high, and it may not be possible to characterize them with measurement equipment normally used for harmonic analysis. It is usually easier to measure with an oscilloscope or transient disturbance monitor.

Three-phase SCR rectifiers (those typically in dc drives, UPS systems, ASDs, etc.) with continuous dc current are the most common cause of voltage notching. The notches occur when the current commutates from one phase to another on the ac side of the rectifier. During this period, there is a momentary short circuit between two phases. The severity of the notch at any point in the system is determined by the source of inductance and the inductance between the rectifier and the point being monitored.

Often, an isolation transformer or 3% impedance ac line reactor (inductor) can be used in the circuit to reduce the effect of notching on the source side. The additional inductance increases the severity of voltage notches at the rectifier terminals (commutation time, or width of the notch, increases with increased commutation reactance); however, most of the notching voltage appears across the ac inductor and notching is less severe on the source side, where other equipment shares a common voltage source.

Steep voltage changes caused by notching can also result in ringing (oscillation) because of capacitances and inductances in the supply circuit. This oscillation can disturb sensitive controls connected to the affected circuit. The high frequencies involved can also cause noise be capacitively coupled to adjacent electrical or communication circuits.

Voltage Flicker

Loads that vary with time, especially in the reactive component, can cause voltage flicker; the varying voltage magnitudes can affect lighting intensity. Arc furnaces are the most common cause of voltage flicker. The envelope of the 60 Hz variations is defined as the flicker signal *V*, and its RMS magnitude is expressed as a percentage of the fundamental. Voltage flicker is measured with respect to sensitivity of the human eye. A typical plot of the 60 Hz voltage envelope characterizing voltage flicker is shown in Figure 28.

The characteristics of voltage flicker are mainly determined by load characteristics and the system short-circuit capacity. For a critical load, it may be necessary to provide a dedicated feed so that it is not on the same circuit with a major load that causes voltage flicker. Using fast switching compensation, such as a static volt-ampere-reactive (VAR) system, or dynamic VAR compensation system, can mitigate the problem. Another method is to effectively increase the short-circuit capacity at the point of common coupling with other loads by using a series capacitor. Protecting the series capacitor during fault conditions requires careful design.

INPUT CURRENT WAVEFORM
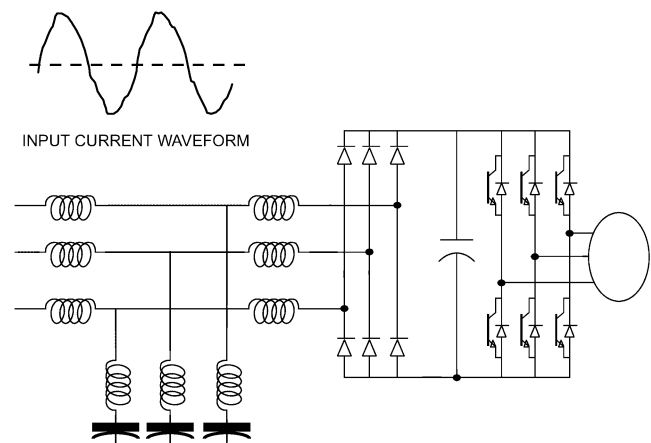
Fig. 27   Example of VFD with Low-Pass Harmonic Filter
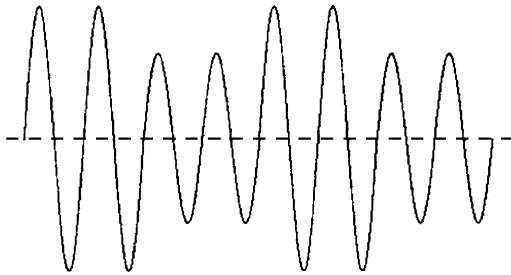
Fig. 28 Example of Flicker

Fig. 29 Example of Electrical Noise

Voltage flicker appears as a modulation of the fundamental frequency (similar to amplitude modulation of an AM radio signal). Therefore, it is easiest to define a magnitude for voltage flicker as the RMS magnitude of the modulation signal, which can be found by demodulating the waveform to remove the fundamental frequency and then measuring the magnitude of the modulation. Typically, magnitudes as low as 0.5% can result in perceptible light flicker if frequencies are in the range of 1 to 10 Hz. Flicker limitations are discussed in ANSI/IEEE *Standard* 146.

Light dimming, another type of light flicker, is caused by starting motors. Large single- or three-phase motors, as used in air conditioners, have the undesirable effect of drawing 6 to 10 times their full load current while starting. This large current, by flowing through system impedances, causes voltage sag that may dim lights.

Noise

Noise, a continuous, unwanted signal on the power circuits (Figure 29), can have a wide variety of different causes (e.g., switching, arcing, electric fields, magnetic fields, radio waves) and can be coupled onto the power circuit in a number of different ways. The noise source and susceptible circuit can be coupled by electric or magnetic fields or by electromagnetic interference (EMI).

The frequency range and magnitude of noise depend on the source that produces the noise. A typical magnitude of noise measured in the voltage is less than 1% of the RMS voltage magnitude. Noise having enough amplitude disturbs electronic equipment such as microcomputers and programmable controllers. Some noise can be eliminated by using an isolation transformer with an electrostatic shield; other noise requires EMI filtering or line conditioners. Wiring and grounding practices also significantly affect the noise levels at particular loads. The appropriate method for controlling noise depends on the methods of coupling, frequency range of the noise, and susceptibility of the equipment being protected.

Inductive (Magnetic) Coupling. Magnetic fields induce currents in conductors. The magnetic fields are caused by current flowing in nearby power conductors, parts of circuits, data lines, or even building structure, and can be temporary or steady state. The actual coupled currents in power conductors and equipment conductors depend on exposure (length of conductor in the field), angle between conductor and field, and magnetic field strength. Conductors carrying large currents and/or with large spacing between conductors can create strong 60 Hz magnetic fields that do not decay quickly with distance from the source. These fields can cause distortion on CRT or TV screens, and may interfere with sensitive electronic (especially analog) devices such as radio-controlled equipment, energy and building automation systems, photoelectric sensors, test and measurement equipment, and data processing equipment. During building design, steps should be taken to minimize generation of strong magnetic fields, and to keep sensitive equipment well separated from these areas.

Current flow in the power system ground can be an important cause of magnetic fields because the loop area between the supply conductor and the return path through the ground can be very large. Therefore, grounding techniques to minimize noise levels
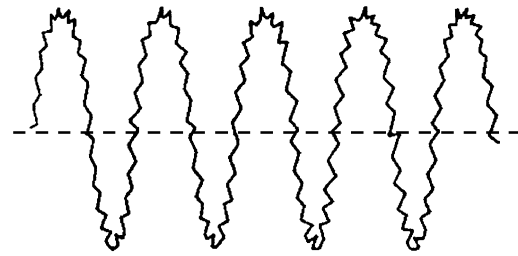
can help reduce magnetic field problems. To minimize interference, power conductors should always be physically separated from control circuit conductors. Magnetic shielding can also help.

Capacitive (Electrostatic) Coupling. Capacitive coupling between conductors results in coupling of transient voltage signals between circuits. Transient voltages with high-frequency components or high rates of rise are the most likely to be capacitively coupled between circuits (the coupling capability of a capacitor increases with frequency). Switch operations, arcing, lightning, or electrostatic discharge can cause these transients. Electric fields capacitively couple voltage between conductors. Strength is measured in volts per metre and may range from very slight to many kilovolts per metre.

High magnitudes of capacitively coupled voltages can affect normal operations of various types of electronic devices, or even cause discharges and damage. Possible solutions include applying shielding and coating, and improving design of power equipment to reduce the generation of high-transient-voltage conditions. To minimize interference, power conductors should always be physically separated from control circuit conductors.

Electromagnetic Interference (EMI). EMI refers to interference caused by electromagnetic waves over a wide range of frequencies. Many interference sources start out as either strongly magnetic or strongly electric, but within about half a wavelength the fields convert to a balanced ratio of electric and magnetic fields (an electromagnetic field). Transients such as electrostatic discharge, arcing, contacts, power electronic switching, fluorescent lighting, and lightning cause electromagnetic waves. Steady-state EMI can occur in the form of radio frequency interference (RFI) from microwave and radar transmissions, radio and TV broadcasts, corona of high-voltage transmission line, arc welding, and other sources that generate radio-frequency electromagnetic waves. Although RFI is not destructive, it can cause a variety of malfunctions of susceptible electronic equipment and can disturb microcomputers and programmable controllers; the level of disturbance depends on the amount of RFI. Solutions include using appropriate shielding or filtering techniques.

BILLING RATES

Equipment specifications state how much electricity is used, but the cost of that electricity is usually the determining factor in HVAC&R system design and equipment selection. Electricity tariffs or rates set prices for

- How much electricity is used; energy (kWh)
- Rate at which electricity is used; demand (kW)
- Quality of electricity used; power factor (VAR or kVAR)

Electric rates are contracts defining what the electricity user will pay for the amounts consumed. Rates may be based on cost, policy, market, or a combination of cost/policy and market. Additionally, rates may be based on either kW or kVA demand. Designers should not assume that the types of rates will remain the same over the life of a building.

Cost-Based Rates

Cost-based rates are designed to charge each class of consumer based on the utility's cost to serve. Costs depend on kilowatt-hours used, maximum demand, and time of day at which electricity is used. A customer class is a group of electricity consumers whose use characteristics are similar; each customer class has a different rate or tariff. Typical customer classes are residential, multi-family, small commercial, large commercial, small industrial, large industrial, electric water heating, electric space heating, street lighting, etc. Cost-based rates are usually predicated on the following assumptions:

- The more electricity a customer uses the less it costs, per kilowatt-hour, to serve that customer.
- The higher the demand of a customer, the more it costs to serve that customer.
- It costs less per kilowatt-hour to serve a customer with a higher load factor. Load factor LF is defined as the customer's average demand divided by the peak demand, or the energy consumed in the billing period divided by the peak demand times the number of hours in the billing period. [LF = kWh used in the billing period/(peak demand × hours in billing period)]
- It costs less for a utility to deliver electricity at times of low system load than at times of high system load.

Energy Charge. The consumer pays the utility a fixed amount for every kilowatt-hour used. Small customers, especially residential, often simply pay for energy used. Certain loads may have usage profiles that allow the utility to provide electricity at times of low production costs (e.g., street lighting) or cost less per kilowatt-hour because the customer uses significantly more than a typical customer (e.g., electric space heating). These loads are often metered separately and are charged a lower cost per kilowatt-hour than general-service usage.

Fuel Adjustment Clause (FAC). A significant part of the cost of electricity is the fuel needed to generate it. In the 1970s, the price of primary energy sources (especially oil) became extremely volatile, and the fuel adjustment clause was designed to accommodate this without requiring frequent rate adjustments. Energy charges with FACs consist of two parts: a fixed charge per kilowatt-hour and a variable charge per kilowatt-hour that depends on the average price of fuel purchased by the power generator. During periods of low fossil fuel prices or high hydro runoff, for example, the FAC results in lower prices to the consumer.

Demand Charge. "Demand" is the maximum rate of use of electricity. It is expressed in kilowatts (kW) or kilovolt-amps (kVA) and is typically measured over 15, 30, or 60 min periods. For example, 1 kWh used in 15 min is equal to 4 kW demand (1 kWh/0.25 hours). Demand charges are designed to cover the system capacity cost to deliver energy to a customer and/or the marginal generation cost to produce electricity at time of highest usage. To deliver electricity to a consumer, a utility must install wires, transformers, and meters; the higher the customer's projected demand, the larger the capacity of wires and transformers serving the customer must be. From a systemwide perspective, the utility must also build enough generation and transmission capacity to serve the system load at its highest peak level. A **noncoincident demand (NCD) charge** is a charge per kilowatt for the customer's maximum demand for electricity (in any 15, 30, or 60 min period) during the billing cycle. Noncoincident demand charges are generally imposed to cover the cost to transform and deliver energy to the consumer. A **coincident demand (CD) charge** (also known as a **peak** or **on-peak demand charge**) is a charge per kilowatt for the customer's maximum demand for electricity in any 15, 30, or 60 min period occurring during times of high system load. For example, in a summer-peaking utility, the demand charge may be applied only to the maximum demand occurring between 11:30 AM and 6:00 PM on weekdays from May to September. CD charges are designed to pay for additional generation and other system reinforcement costs needed to meet peak demands.

Ratcheted Demand Charge. Demand charges may be calculated based on the customer's maximum demand during each billing cycle, or the maximum demand during the 12 mo preceding the electricity bill. A high demand in one month "ratchets" the demand charge up for some or all of the following 11 months.

Seasonal Rate. Some utilities' generation costs vary significantly from one season to another. For example, spring runoff may yield more low-cost hydroelectric energy, or high summer air-conditioning loads may result in more power generation by less efficient peaking plants. A seasonally adjusted rate reflects this by setting different kilowatt and/or kilowatt-hour charges for different seasons.

Time of Use (TOU) Rate. A utility's average production cost for electricity usually varies with the total system load. As demand increases, less efficient (i.e., more costly) generators are used. Increasing peak loads also require that a utility invest in greater generation, transmission, and distribution capacity to meet the peak. A TOU rate is designed to recover the increased production or capacity costs during times of system peak. Electricity use is recorded by multiregister meters and priced at different levels, depending on whether the peak/off-peak or peak/shoulder/off-peak model is used. TOU rates are usually designed not only to "recover" time-differentiated production costs, but also to induce consumers to shift their electricity usage from peak periods to times of lower system load. In this way, TOU rates are both "cost-based" and "policy-based." Thermal energy storage (TES) systems are one method for consumers to reduce their on-peak demand or energy charges and to consume electricity during lower-cost, off-peak times. With TES, a consumer may use the same or more total electricity but will pay less for it.

Declining Block Rate. In designing cost-based rates, the cost to serve is usually inversely proportional to the amount consumed. To reflect this, energy may be priced according to a declining block rate, where the cost per kilowatt-hour decreases as usage increases. For example, a residential customer may pay $0.12/kWh for the first 800 kWh used in a month, $0.10/kWh for the next 550 kWh, and $0.08/kWh for all electricity above 1350 kWh.

Demand-Dependent Block Rate. For larger customers, the size of the blocks of a block rate may depend on the measured demand. For example, a commercial consumer may pay $0.12/kWh for the first 75 kWh per kilowatt of billing demand, $0.10/kWh for the next 150 kWh per kilowatt of billing demand, and $0.08/kWh for every kWh above 225 kWh per kilowatt of billing demand.

Load Factor Penalty. Utilities recover their fixed costs (e.g., capital cost of a transformer) as well as production costs through energy (kWh) charges as well as demand charges. If a consumer's load factor is less than expected, then the utility's kilowatt-hour revenues may not be sufficient to recover its fixed costs. This may occur for a customer with self-owned on-site generation who relies on the utility mainly when the on-site generator is being maintained. In this case, the utility may impose a load factor penalty or surcharge.

Power Factor Penalty. A power system is more efficient and stable when all three phases are equally loaded (balanced) and serving pure resistive load (100% power factor). Some inductive loads, such as most lighting and motors, require reactive power, which may be more difficult and expensive for the utility to supply. Moreover, reactive power (kVAR) is not always measured, and therefore not billed, by typical kilowatt-hour meters. Therefore, utilities often impose a power factor penalty or surcharge on customers with very reactive or inductive loads (power factor not close to 100%) to pay for the VARs that it must supply.

Customer Charge. This is a monthly, usually fixed charge that a consumer must pay, regardless of whether any electricity is used, for being a customer of a utility. This charge typically covers customer services such as the costs of billing, metering, and customer support services, such as call centers.

Connection Fee. When electric service is initiated, especially when construction (additional distribution lines, substations,

distribution transformers, etc.) is required, the utility may charge a connection fee. For example, a utility may charge a residential customer a fixed cost per foot of distribution line that must be constructed beyond an initial 500 ft of line. Some customers may require redundant facilities to ensure reliable service (e.g., a second feeder and load transfer switch for a hospital). The utility would probably include such costs in its connection fee.

Policy-Based Rates

Policy-based rates are designed to encourage consumers to modify their energy use to better conform with the objectives of the utility or legislative or regulatory body (e.g., using nonpolluting or renewable energy sources, deferring grid expansion or generator construction by shifting electricity demand from peak periods, better using waste heat from industrial processes, etc.). It can be argued that some policy-based rates are in fact cost-based, but they incorporate "externalities," or external costs that cannot be directly allocated to a consumer's electricity use. The time of use rate could fall under either category.

Inverted Block Rate. The marginal cost to provide an existing customer with additional energy decreases as energy use per kilowatt of connected load increases. However, additional energy use often hastens the need to construct new generation facilities. An inverted block rate motivates the consumer to reduce energy use by charging less for the first kilowatt-hour used. For example, a residential consumer may pay $0.08 for the first 850 kWh per month, $0.10 for the next 500 kWh, and $0.12 for all usage above 1350 kWh. As with the declining block rate, the break points between "blocks" may be based on demand for that billing cycle.

Lifeline Rate. Lifeline rates are designed so poor consumers will still be able to afford necessary electricity (e.g., enough for refrigeration, lights, adequate heat in winter, etc.). For example, a consumer pays a subsidized price per kilowatt-hour for a minimal amount of electricity and the market rate for any usage above the minimum (e.g., $0.04/kWh for the first 675 kWh and $0.12/kWh for usage above 675 kWh/month).

Net Metering. This is applicable for consumers who own their own on-site generation, still buy electricity from the grid, but sometimes can generate more electricity than is needed in their facility. Net metering is a contract in which the customer pays the utility for the net electricity purchased (i.e., excess on-site generation is sold to the grid and offsets what the customer owes the utility for purchases from the grid).

Green Power Rate. Customers may sign up for blocks of electricity produced by renewable sources, such as wind turbines. Because of electricity from such sources usually costs more than electricity produced by conventional generation, the green energy is sold at a premium.

Surcharges. Government agencies may add special surcharges to electric bills to provide funding for specific energy-related or general-purpose programs. For example, in the United States, many state governments collect public benefit funds through electric bills to provide money for energy efficiency, renewable energy, low-income weatherization, and research programs. Other surcharges may be for power plant upgrades or putting electric distribution lines underground. Surcharges can be fixed or charged on a per-kWh basis. Some surcharges may be capped at a specific dollar amount per type of customer.

Taxes. Government agencies may collect sales and other specific taxes through utility bills. The taxes may be calculated as a percentage total of the entire bill, or on a per-kWh basis (such as $0.001 per kWh). For some customers, taxes and surcharges may comprise a significant portion of the total bill.

Market-Based Rates

Electric utilities are restructuring to disaggregate electricity production, transmission, and distribution and open the market to competition. The theory is that a competitive electricity sector, governed by market rules, is more efficient, lower-cost, and more congruent with consumer needs than regulated electric utilities. Market-based rates are not new, but they are becoming more prevalent. Rates tend to be volatile, and are structured as a contract between the consumer and energy supplier, rather than as a traditional tariff. As a result, they tend to be more customer-specific than uniform over a customer class.

Real-Time Pricing (RTP). Under this scheme, the cost of electricity varies with each hour. The supplier sets a price for electricity based on its forecasted cost to produce or provide the electricity. Hour-by-hour prices are communicated to the customer from 1 to 24 h in advance, and the consumer decides what, if any, action to take in response to the forecasted prices. The most common RTP programs send prices to consumers each evening, to cover the next day. Some programs send prices 4 h in advance, and several also allow 1 h alerts for "surprise" prices during system emergencies or forced outages. Consumers who were on a demand (kilowatt) and energy (kilowatt-hour) rate often are billed only for energy use (kilowatt-hour) on RTP, because the hourly energy cost incorporates the demand charge. The RTP may only apply to the generation portion of the electric bill if transmission and distribution charges are still regulated.

Fixed Pricing. Some consumers in a deregulated market may opt for fixed prices for their electric supply. In these situations, the consumer may pay a price that is higher or lower than the RTP or spot prices. With this type of pricing, the burden of price risk goes to the supplier, who may charge a risk premium to the customer.

Spot Pricing. Consumers in some regions may purchase some or all of their electricity on the spot market, based on the current marginal cost of electricity. This is done through a power exchange, with the consumer either contracting directly with the exchange or going through a third-party electricity broker. Consumers may also purchase electricity through a combination of long-term contracts and spot market purchases.

Interruptible Rates and Responsive Loads. At times of high marginal electricity costs, it may be more cost-effective for a utility to pay its customers to reduce electricity consumption than to contract for additional electricity supplies. With interruptible rates, a consumer agrees to reduce power consumption to or below an agreed-upon level (or go off-line) when requested to do so by the utility, in return for a lower price. The utility's requests may be limited in number of times per year (or month) the consumer can be asked to reduce load, maximum duration of the load reduction, and minimum notice required (typically 1 to 4 h) before electric load is reduced. In other cases, there is no limit to the number or length of utility requests.

Direct Load Control. This is similar to interruptible load, but instead of the consumer's complying with the utility's request, the utility can exercise direct control over the consumer's appliances. Appliances commonly contracted for load control programs are water heaters, swimming pool pumps, air conditioners, heat pumps, resistance space heat, and controllable thermostats for HVAC&R systems. The tariff usually is in the form of a monthly rebate or fixed bill credit for each controllable appliance.

Performance-Based Rates. These are designed to ensure that the consumer receives acceptable quality and reliability of electric supply. The utility and consumer agree on a minimum standard for service quality in terms of number and duration of outages, voltage sags and swells, harmonic levels, or other transient phenomena. If these minimum service quality levels are not met, the utility must rebate money to the consumer; the amount rapidly increases as performance or service quality declines. In some cases, the rate, or type of rate charged, may not change, but customers receive bill credits or rebates based on a reduction in the electric company's rate of return.

Performance Contracting. In performance contracting, a consumer contracts with a third party to pay for the end-use applications of electricity. This usually involves an agreement where the performance contractor [often called an energy service company (ESCO)] installs and sometimes operates and maintains improved equipment for HVAC&R systems, lighting, building or process energy management, etc. The consumer's payments are indexed to successful equipment performance. That performance is often evaluated in terms of the facility's utility bills and calculated cost savings comparing the actual energy costs with estimates of what the costs would have been without the ESCO's intervention. A more detailed explanation of performance contracting is presented in ASHRAE *Guideline* 14-2002.

CODES AND STANDARDS

NEC®

The National Electrical Code® (NEC) is devised and published by the National Fire Protection Association, a consensus standards writing industry group. It is revised every three years. The code exists in several versions: the full text, an abridged edition, and the NEC Handbook (which contains the authorized commentary on the code, as well as the full text). It sets minimum electrical safety standards, and is widely adopted.

UL Listing

Underwriters Laboratories (UL), formerly an insurance industry organization, is now independent and nonprofit. It tests electrical components and equipment for potential hazards. When a device is UL-listed, UL has tested the device, and it meets their requirements for safety (i.e., fire or shock hazard). It does not necessarily mean that the device actually does what it is supposed to do. The UL does not have power of law in the United States; non-UL-listed devices are legal to install. However, insurance policies may have clauses that limit their liability in a claim related to failure of a non-UL-listed device. The NEC requires that a wiring component used for a specific purpose is UL-listed for that purpose. Thus, certain components must be UL-listed before inspector approval and/or issuance of occupancy permits.

CSA Approved

The Canadian Standards Association (CSA) is made up of various government agencies, power utilities, insurance companies, electrical manufacturers, and other organizations. They update CSA *Standard* C22.1, the Canadian Electrical Code (CEC), every two or three years.

The Canadian Standards Association (or recognized equivalent) must certify every electrical device or component before it can be sold in Canada. Implicit in this is that all wiring must be done with CSA-approved materials. Testing is similar to UL testing (a bit more stringent), except that CSA approval is required by law. Like the UL, if a fire is caused by non-CSA-approved equipment, the insurance company may not pay the claim.

ULC

Underwriters Laboratory of Canada (ULC) is an independent organization that undertakes the quarterly inspection of manufacturers to ensure continued compliance of UL listed/recognized products to agency reports and safety standards. This work is done under contract to UL, Inc.; they are not a branch or subsidiary of UL.

NAFTA Wiring Standards

Since the North America Free Trade Agreement (NAFTA) came into effect on January 1, 1994, CSA approval of a device is legally considered equivalent to UL approval in the United States, and UL listing is accepted as equivalent to CSA approval in Canada. Devices marked only with UL approval are acceptable in the CEC, and CSA approval by itself of a device is accepted by the NEC. This allows much freer trade in electrical materials between the two countries. This does not affect the electrical codes themselves, so differences in practice between the NEC and CEC remain.

IEEE

The Institute of Electrical and Electronic Engineers' *Standard* 519 suggests limits for both harmonic current and voltage distortion, based on electrical system conditions.

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CHAPTER 56

ROOM AIR DISTRIBUTION

ROOM air distribution systems, like other HVAC systems, are intended to achieve required thermal comfort and ventilation for space occupants and processes. Although air terminals (inlets and outlets), terminal units, local ducts, and the rooms themselves may affect room air distribution, this chapter addresses only air terminals and their effect on occupant comfort. This chapter is intended to help HVAC designers apply air distribution systems to occupied spaces, providing information on characteristics of various air distribution strategies, and tools and guidelines for applications and system design. Naturally ventilated spaces are not addressed; see Chapter 27 of the 2005 *ASHRAE Handbook—Fundamentals* for details. Also see Chapter 33 of the 2005 *ASHRAE Handbook—Fundamentals* for more information on space air diffusion; Chapter 17 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment* for information on room air distribution equipment; and Chapter 47 of this volume for sound and vibration control guidance.

Room air distribution systems can be classified by (1) their primary objective and (2) the method by which they attempt to accomplish that objective. The objective of any air distribution system can be classified as one of the following:

- Conditioning and/or ventilation of the space for occupant thermal comfort
- Conditioning and/or ventilation to support processes within the space
- A combination of these

As a general guideline, the **occupied zone** in a space is any location where occupants normally reside, and may differ from project to project; it is application-specific, and should be carefully defined by the designer. The occupied zone is generally considered to be the room volume between the floor level and 6 ft above the floor. Standards and guidelines, such as ANSI/ASHRAE *Standards* 55 and 62.1, further define the occupied zone (e.g., *Standard* 55 exempts areas near walls).

Occupant comfort is defined in detail in ANSI/ASHRAE *Standard* 55-2004. Figure 5.2.1.1 of the *Standard* shows acceptable ranges of temperature and humidity for spaces. As a general guide, 80% of occupants in typical office spaces can be satisfied with thermal environments over a wide range of temperatures and relative humidities. Designers often target indoor dry-bulb temperatures between 73 and 77°F, relative humidities between 25 and 60%, and occupied zone air velocities below 50 fpm. ANSI/ASHRAE *Standard* 113 describes a method for evaluating effectiveness of various room air distribution systems in achieving thermal comfort.

Room air distribution methods can be classified as one of the following:

- **Mixed systems** (e.g., overhead distribution) have little or no thermal stratification of air in the occupied and/or process space.
- **Full thermal stratification systems** (e.g., thermal displacement ventilation) have little or no air mixing in the occupied and/or process space.

- **Partially mixed systems** (e.g., most underfloor air distribution designs) provide limited air mixing in the occupied and/or process space.
- **Task/ambient air distribution** (e.g., personally controlled desk outlets, spot conditioning systems) focuses on conditioning only part of the space for thermal comfort and/or process control.

Because task/ambient design requires a high degree of individual control, it is not covered in this chapter; see Chapter 33 of the 2005 *ASHRAE Handbook—Fundamentals* for details. Limited design guidance is also provided by Bauman and Daly (2003).

Figure 1 illustrates the spectrum between the two extremes (full mixing and full stratification) of room air distribution strategies.

SYSTEM DESIGN

Design Constraints

Space design constraints affect room air distribution system choices and how air inlets and outlets are used. Space constraints may include the following:

- Dimensions
- Heat gain and loss characteristics
- Use
- Acoustical requirements
- Available locations for air inlets and outlets

Inlet and outlet characteristics are discussed in Chapter 17 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*. This chapter discusses more specific application considerations for air inlets and outlets.

Sound

Sound emitted from inlets and outlets is directly related to the airflow quantity and free area velocity. The airflow sound intensity in a space also depends on the room's acoustical absorption and the observer's distance from air distribution devices, For more information, see Chapter 47 of this volume and Chapter 7 in the 2005 *ASHRAE Handbook—Fundamentals*.

Inlet Conditions to Air Outlets

The way an airstream approaches an outlet is important. For good air diffusion, the inlet configuration should create a uniform discharge velocity profile from the outlet, or the outlet may not perform as intended.

The outlet usually cannot correct effects of improper duct approach. Many sidewall outlets are installed either at the end of vertical ducts or in the side of horizontal ducts, and most ceiling outlets are attached either directly to the bottom of horizontal ducts or to special vertical takeoff ducts that connect the outlet with the horizontal duct. In all these cases, devices for directing and equalizing the airflow may be necessary for proper direction and diffusion of the air.

Return Air Inlets

The success of a mixed air distribution system depends primarily on supply diffuser location. Return grille location is far

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The preparation of this chapter is assigned to TC 5.3, Room Air Distribution.
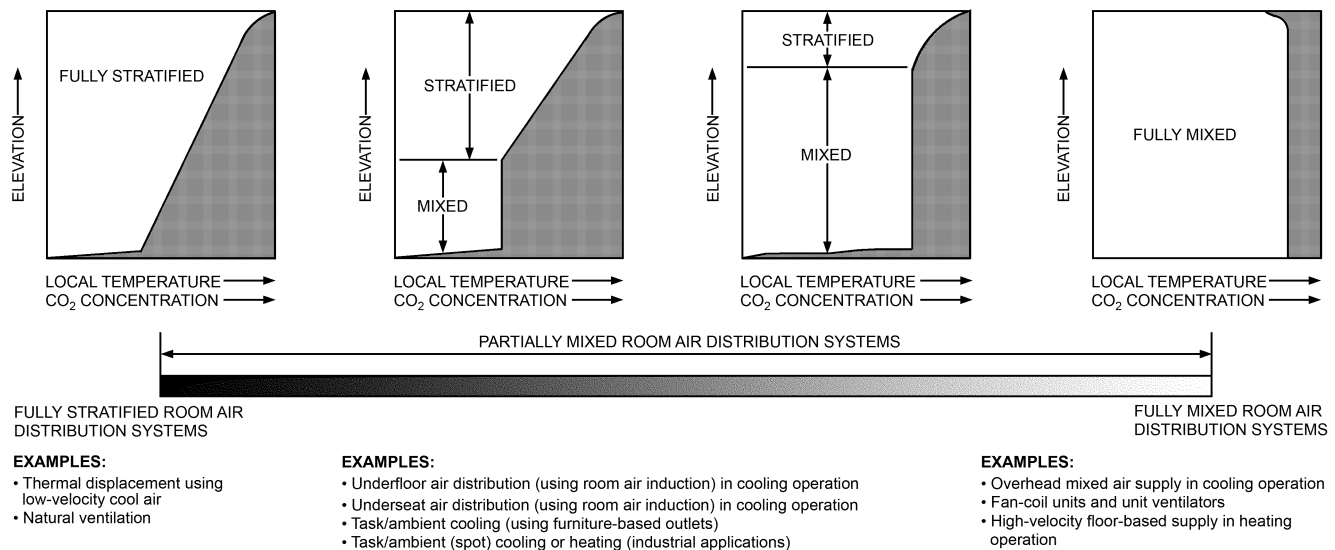
Fig. 1   Classification of Air Distribution Strategies

EXAMPLES:
• Thermal displacement using
  low-velocity cool air
• Natural ventilation

EXAMPLES:
• Underfloor air distribution (using room air induction) in cooling operation
• Underseat air distribution (using room air induction) in cooling operation
• Task/ambient cooling (using furniture-based outlets)
• Task/ambient (spot) cooling or heating (industrial applications)

EXAMPLES:
• Overhead mixed air supply in cooling operation
• Fan-coil units and unit ventilators
• High-velocity floor-based supply in heating
  operation

Table 1   Recommended Return Inlet Face Velocities

Inlet Location	Velocity Across Gross Area, fpm
Above occupied zone	>800
In occupied zone, not near seats	600 to 800
In occupied zone, near seats	400 to 600
Door or wall louvers	200 to 300
Through undercut area of doors	200 to 300

less critical than with outlets. In fact, the return air intake affects room air motion only immediately around the grille. Measurements of velocity near a return air grille show a rapid decrease in magnitude as the measuring device is moved away from the grille face. Table 1 shows recommended maximum return air grille velocities as a function of grille location. Every enclosed space should have return/transfer inlets of adequate size per this table.

For stratified and partially mixed air distribution systems, there are advantageous locations for return air inlets. For example, an intake can be located to return the warmest air in cooling season.

If the outlet is selected to provide adequate throw and directed away from returns or exhausts, supply short-circuiting is normally not a problem. The success of this practice is confirmed by the availability and use of combination supply and return diffusers.

Indoor Air Quality and Sustainability

Air distribution systems affect not only IAQ and thermal comfort, but also energy consumption over the entire life of the project; choices made early in the design process are important. ANSI/ASHRAE/IESNA *Standard* 90.1 provides energy efficiency requirements that affect supply air characteristics. The U.S. Green Building Council's (USGBC) Leadership in Energy and Efficient Design (LEED™) rating system was originally created in response to indoor air quality concerns, and the latest versions of their *New Construction and Major Renovations Guide* include prerequisites and credits for increasing ventilation effectiveness and improving thermal comfort. These requirements and optional points are relatively easy to achieve if good room air distribution design principles, methods, and standards are followed.

Environmental tobacco smoke (ETS) control is a LEED prerequisite. Banning indoor smoking is a common approach, but if indoor smoking is to be allowed, ANSI/ASHRAE *Standard* 62.1-2004 requires that more than the base non-ETS ventilation air be provided where ETS is present in all or part of a building. Rock (2006) provides additional advice on dealing with ETS.

Ventilation effectiveness is affected directly by the room air distribution system's design, construction, and operation, but is very difficult to predict. Many attempts have been made to quantify ventilation effectiveness, including ASHRAE *Standard* 129. However, this standard is only for experimental tests in well-controlled laboratories and should not be applied directly to real buildings.

Because of the difficulty in predicting ventilation effectiveness, ANSI/ASHRAE *Standard* 62.1 provides a table of typical values that were determined through the experiences of its Standard Project Committee and reviewers or extracted from research literature; for example, well-designed ceiling-based air diffusion systems produce near perfect air mixing, when in cooling mode, and as such they yield an air change effectiveness of almost 1.0. More information on ANSI/ASHRAE *Standard* 62.1 is available in its user's manual (ASHRAE 2004).

Displacement and underfloor air distribution (UFAD) systems have the potential for values greater than 1.0. More information on ceiling- and wall-mounted air inlets and outlets can be found in Rock and Zhu (2002). Performance of displacement systems is described by Chen and Glicksman (2003), and UFAD is discussed in detail by Bauman and Daly (2003).

Air terminals, such as diffusers or grilles, may become unsightly over time because of accumulation of dirt on their faces (smudging). Instead of replacing air terminals, and thus requiring new materials and energy for manufacturing, they can often be cleaned in place to restore their appearance. Those that cannot be cleaned and must be replaced should be recycled, not discarded, to recover the various metals and other desirable materials of construction.

MIXED AIR DISTRIBUTION

In mixed air systems, high-velocity supply jets from air outlets maintain comfort by mixing room air with supply air. This air mixing, heat transfer, and resultant velocity reduction should occur outside the occupied zone. Occupant comfort is maintained not directly by motion of air from outlets, but from secondary air motion from mixing in the unoccupied zone. Comfort is maximized when uniform temperature distribution and room air velocities of less than 50 fpm are maintained in the occupied zone.

Maintaining velocities less than 50 fpm in the occupied zone is often overlooked by designers, but is critical to maintaining comfort. The outlet's selection, location, supply air volume, discharge velocity, and air temperature differential determine the resulting air motion in the occupied zone.

Principles of Operation

Mixed systems generally provide comfort by entraining room air into discharge jets located outside occupied zones, mixing supply and room air. Ideally, these systems generate low-velocity air motion (less than 50 fpm) throughout the occupied zone to provide uniform temperature gradients and velocities. Proper selection of an air outlet is critical for proper air distribution; improper selection can result in room air stagnation, unacceptable temperature gradients, and unacceptable velocities in the occupied zone that may lead to occupant discomfort.

The location of a discharge jet relative to surrounding surfaces is important. Discharge jets attach to parallel surfaces, given sufficient velocity and proximity. When a jet is attached, the throw increases by about 40% over a jet discharged in an open area. This difference is important when selecting an air outlet. For detailed discussion of the surface effect on discharge jets, see Chapter 33 of the 2005 *ASHRAE Handbook—Fundamentals*.

Space Ventilation and Contaminant Removal

These systems are intended to maintain acceptable indoor air quality by mixing supply and room air (dilution ventilation). Supply air is typically a conditioned mixture of ventilation and recirculated air. Outlet type and discharge velocity determine the mixing rate of the space and should be a design consideration. The room's return or exhaust air carries away diluted air contaminants. Space air ventilation rates are mandated under ASHRAE *Standard* 62.1-2004, but supply airflow rates are often higher because of thermal loads.

Benefits and Limitations

Benefits of fully mixed systems include the following:

- Most office applications can use lower supply dry-bulb temperatures, for smaller ductwork and lower supply air quantities.
- Air can be supplied at a lower moisture content, possibly eliminating the need for a more complex humidity control system.
- Vertical temperature gradients are lower for cooling applications with high internal heat gains, which may improve thermal comfort.
- Mixed systems are the most common design for distribution systems, because designers and installers are familiar with the required system components and installation.

Limitations of mixed systems include the following:

- Partial-load operation in variable-air-volume (VAV) systems may reduce outlet velocities, reducing room air mixing and compromising thermal comfort. Designers should consider this when selecting outlets.
- Cooling and heating with the same ceiling or high-sidewall diffuser may cause inadequate performance in heating mode and/or excessive velocity in cooling mode.
- Ceilings more than 12 ft high may require special design considerations to provide acceptable comfort in the occupied zone. Care should be taken to select the proper outlet for these applications.
- Because mixed systems typically use high-velocity jets of air, any obstructions in the space (e.g., bookshelves, wall partitions, furniture) can reduce comfort.
- Lighter-than-air contaminants are uniformly mixed in the space and typically result in higher contaminant concentrations, which may compromise indoor air quality.

Mixed air systems typically use either ceiling or sidewall outlets discharging air horizontally, or floor- or sill-mounted outlets discharging air vertically. They are the most common method of air distribution in North America.

Horizontal Discharge Cooling with Ceiling-Mounted Outlets

Ceiling-mounted outlets typically use the surface effect to transport supply air in the unoccupied zone. The supply air projects
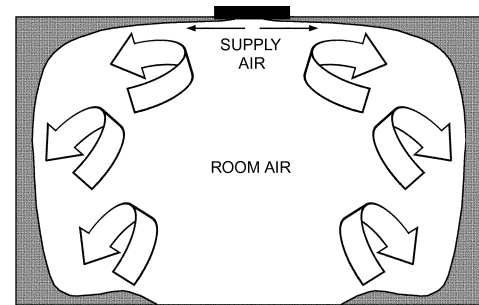
Fig. 2   Air Supplied at Ceiling Induces Room Air into Supply Jet

across the ceiling and, with sufficient velocity, can continue down wall surfaces and across floors, as shown in Figure 2. In this application, supply air should remain outside the occupied zone until it is adequately mixed and tempered with room air. Air motion in the occupied zone is generated by room air entrainment into the supply air (Nevins 1976).

Overhead outlets may also be installed on exposed ducts, in which case the surface effect does not apply. Typically, if the outlet is mounted 1 ft or more below a ceiling surface, discharge air will not attach to the surface. The unattached supply air has a shorter throw and can project downward, resulting in high air velocities in the occupied zone. Some outlets are designed for use in exposed duct applications. Typical outlet performance data presented by manufacturers are for outlets with surface effect; consult manufacturers for information on exposed duct applications.

Vertical-Discharge Cooling or Heating with Ceiling-Mounted Outlets

Vertically projected outlets are typically selected for high-ceiling applications that require forcing supply air down to the occupied zone. It is important to keep cooling supply air velocity below 50 fpm in the occupied zone. For heating, supply air should reach the floor.

There are outlets specifically designed for vertical projection and it is important to review the manufacturer's performance data notes to understand how to apply catalog data. Throws for heating and cooling differ and also vary depending on the difference between supply and room air temperatures.

Cooling with Sidewall Outlets

Sidewall outlets are usually selected when access to the ceiling plenum is restricted. Sidewall outlets within 1 ft of a ceiling and set for horizontal or a slightly upward projection the sidewall outlet provide a discharge pattern that attaches to the ceiling and travels in the unoccupied zone. This pattern entrains air from the occupied zone to provide mixing.

In some applications, the outlet must be located 2 to 4 ft below the ceiling. When set for horizontal projection, the discharge at some distance from the outlet may drop into the occupied zone. Most devices used for sidewall application can be adjusted to project the air pattern upwards toward the ceiling. This allows the discharge air to attach to the ceiling, increasing throw distance and minimizing drop. This application provides occupant comfort by inducing air from the occupied zone into the supply air.

Some outlets may be more than 4 ft below the ceiling (e.g., in high-ceiling applications, the outlet may be located closer to the occupied zone to minimize the volume of the conditioned space). Most devices used for sidewall applications can be adjusted to project the air pattern upward or downward, which allows the device's throw distance to be adjusted to maximize performance.

When selecting sidewall outlets, it is important to understand the manufacturer's data. Most manufacturers offer data for outlets

tested with surface effect, so they only apply if the device is set to direct supply air toward the ceiling. When the device is 4 ft or more below a ceiling, or supply air is directed horizontally or downward, the actual throw distance of the device is typically shorter. Many sidewall outlets can be adjusted to change the spread of supply air, which can significantly change throw distance. Manufacturers usually publish throw distances based on specific spread angles.

Cooling with Floor-Mounted Air Outlets

Although not typically selected for nonresidential buildings, floor-mounted outlets can be used for mixed system cooling applications. In this configuration, room air from the occupied zone is induced into the supply air, providing mixing. When cooling, the device should be selected to discharge vertically along windows, walls, or other vertical surfaces. Typical nonresidential applications include lobbies, long corridors, and houses of worship.

It is important to select a device that is specially designed for floor applications. It must be able to withstand both the required dynamic and static structural loads (e.g., people walking on them, loaded carts rolling across them). Also, many manufacturers offer devices designed to reduce the possibility of objects falling into the device. It is strongly recommended that obstructions are not located above these in-floor air terminals, to avoid restricting their air jets.

Long floor-mounted grilles generally have both functioning and nonfunctioning segments. When selecting air outlets for floor mounting, it is important to note that the throw distance and sound generated depend on the length of the active section. Most manufacturers' catalog data include correction factors for length's effects on both throw and sound. These corrections can be significant and should be evaluated. Understanding manufacturers' performance data and corresponding notes is imperative.

Cooling with Sill-Mounted Air Outlets

Sill-mounted air outlets are commonly used in applications that include unit ventilators and fan coil units. The outlet should be selected to discharge vertically along windows, walls, or other vertical surfaces, and project supply air above the occupied zone.

As with floor-mounted grilles, when selecting and locating sill grilles, consider selecting devices designed to reduce the nuisance of objects falling inside them. It is also recommended that sills be designed to prevent them from being used as shelves.

Heating and Cooling with Perimeter Ceiling-Mounted Outlets

When air outlets are used at the perimeter with vertical projection for heating and/or cooling, they should be located near the perimeter surface, and selected so that the published 150 fpm isothermal throw extends at least halfway down the surface or 5 ft above the floor, whichever is lower. In this manner, during heating, warm air mixes with the cool downdraft on the perimeter surface, to reduce or even eliminate drafts in the occupied space.

If a ceiling-mounted air outlet is located away from the perimeter wall, in cooling mode, the high-velocity cool air reduces or overcomes the thermal updrafts on the perimeter surface. To accomplish this, the outlet should be selected for horizontal discharge toward the wall. Outlet selection should be such that isothermal throw to the terminal velocity of 150 fpm should include the distance from the outlet to the perimeter surface. For heating, the supply air temperature should not exceed 15°F above the room air temperature.

Space Temperature Gradients and Airflow Rates

A fully mixed system creates homogeneous thermal conditions throughout the space. As such, thermal gradients should not be expected to exist in the occupied zone. Improper selection, sizing, or placement may prevent full mixing and can result in stagnant areas, or having high-velocity air entering the occupied zone.

Supply airflow requirements to satisfy space sensible heat gains or losses are inversely proportional to the temperature difference between supply and return air. The following equation can be used to calculate space airflow requirements (at standard conditions):

$$Q = \frac{q_s}{1.08(t_r - t_s)} \tag{1}$$

where

Q = required supply airflow rate to meet sensible load, cfm
q_s = net sensible heat gain in the space, Btu/h
t_r = return or exhaust air temperature, °F
t_s = supply air temperature, °F

For fully mixed systems with conventional ceiling heights, the return (or exhaust) and room air temperatures are the same; for example, a room with a set-point temperature of 75°F has, on average, a 75°F return or exhaust air temperature.

Methods for Evaluation

The objective of air diffusion is to create the proper combination of room air temperature, humidity, and air motion in the occupied zone to provide thermal comfort and acceptable indoor environmental quality. There are three recommended methods of selecting outlets for mixed air systems using manufacturers' data:

- By appearance, flow rate, and sound data
- By isovels (lines of constant velocity) and mapping
- By comfort criteria

These selection methods are not meant to be independent. It is the designer's choice as to which to start with, but it is recommended that at least two methods be used for any design.

Variation from accepted thermal limits (ASHRAE *Standard* 55), lack of uniform thermal conditions in the space, or excessive fluctuation of conditions in one part of the space may produce discomfort. Thermal discomfort also can arise from any of the following conditions:

- Excessive air motion (draft)
- Excessive room air temperature stratification (horizontal, vertical, or both)
- Failure to deliver or distribute air according to load requirements at different locations
- Rapid fluctuation of room temperature

Selection

By Appearance, Flow Rate, and Sound Data. For a given appearance, flow rate, pressure drop, and sound level criteria, designers can select outlets from manufacturers' catalogs, using the following steps:

1. Determine air volumetric flow requirements based on load and room size. For VAV systems, evaluation should include the range of flow rates from minimum occupied to design load.
2. Determine acceptable outlet noise criterion (NC); consult Chapter 47 of this volume, or Chapter 7 in the 2005 *ASHRAE Handbook—Fundamentals*.
3. Locate a range of products from manufacturers' catalogs that meet the airflow and NC requirements. Multiple outlets in a space at the same cataloged NC, and other design considerations, may result in actual sound levels greater than cataloged values. Manufacturers' data are obtained using ideal inlet conditions, and may vary from field installations. From experience,

   - For identical outlets 10 ft or more apart, the cataloged NC rating applies.
   - Identical outlets within 10 ft of each other add no more than 3 dB to the sound pressure level.
   - For continuous linear outlets, only the sound produced by the closest 10 ft need be considered.

Table 2 Effect of Neck-Mounted Damper on Air Outlet NC

Total Pressure Ratio*	100%	150%	200%	400%
dB Increase	0	4.5	8	16

*Ratio of air pressure before and after damper.

- A wide-open damper installed in the neck of a diffuser can add 4 to 5 NC to the cataloged NC value.
- Significantly closed balancing dampers can add more than 10 NC, depending on duct pressure and how far upstream it is installed. Table 2 gives an example.

4. Select air terminals from manufacturers' catalogs that meet aesthetic and physical needs.

Although these selections may meet the sound requirements for a project, the results do not fully address occupant comfort. Without evaluating the throw of the outlets or room air mixing, this selection method may result in excessive air velocities in the occupied zone, or limited mixing and resultant stagnation. It is recommended that the designer consider selection by isovel mapping or by comfort criteria in addition to selection by appearance, flow rate, and sound data. Either of these methods addresses resulting air motion in the occupied zone and occupant comfort.

By Isovels and Mapping. Using manufacturers' catalog throw data, a designer can predict the path of an outlet's discharge jet. Most manufacturers' catalogs list the distance a jet travels to reach a terminal velocity of 150 to 50 fpm. With this information, the designer can map the path of the discharge jet for a given outlet. This evaluation can prevent problems such as excessively high air velocities in the occupied zone, or stagnation in a given area. Note that most manufacturers' throw data are based on isothermal supply air; the supply jet temperature is equal to the room air temperature. When using this mapping method, consider the positive or negative buoyancy of nonisothermal (heated or cooled) supply air. In both heating and cooling, a discharge jet should travel the distance shown in the catalog to a terminal velocity of 150 fpm without much influence from buoyancy. When evaluating a jet at lower terminal velocities (e.g., 100 or 50 fpm), consider buoyancy's effect on the distance the jet will travel.

A cool air jet travels less far along a horizontal surface than an isothermal jet does. If an outlet is selected so that the horizontal jet does not have enough velocity to reach a vertical surface, the jet can separate from the horizontal surface and project down into the occupied zone, causing drafts and discomfort. Manufacturers' tables show the drop of a cool air jet so the designer can predict the resulting path.

When evaluating heated air, the designer should consider the positive buoyancy of the discharge jet. A heated jet projecting along a horizontal surface or in an upward vertical pattern travels farther than an isothermal jet. In downward vertical discharge, a heated jet travels a shorter distance than an isothermal jet.

Combining selection by isovels and mapping with acoustical selection allows discharge jet location and intensity in a space to be predicted. Outlet selection should be evaluated at the space's typical operating points (i.e., maximum heating and cooling, and minimum heating and cooling). The following steps may be used:

1. Identify the occupied zone for the space.
2. Select outlet(s) that meet design NC, pressure drop, and flow rate requirements. Identify the supply jet location using cataloged throw data.
3. Evaluate air jet mapping to ensure terminal velocities in the occupied zone do not exceed 50 fpm.
4. For overhead heating applications, $\Delta t < 15°F$ (see Chapter 33 of the 2005 *ASHRAE Handbook—Fundamentals*), evaluate the diagram to ensure that jet velocities 5 ft from the floor are at least 150 fpm.

Other design considerations include the following:

- In multiple-outlet applications, jets should not collide to cause a downward projection of air resulting in velocities greater than 50 fpm in the occupied zone.
- For VAV applications, consider both minimum and maximum flow conditions.

Selection by Comfort Criteria T_{50}/L. Selection by isovels and mapping is effective at predicting the path of the discharge jet from an outlet and evaluating resultant occupant comfort. However, there is an established method to quantify occupant comfort during cooling conditions, based on space dimensions and isothermal catalog throw data. This method can be used to predict a space's resulting air diffusion performance index (ADPI).

The comfort criteria T_{50}/L method was developed to predict occupant comfort during cooling conditions, using manufacturers' isothermal catalog throw data (*T*, usually for 50 fpm terminal velocity) and the dimensions available for throw (*L*) on the plan view of a mechanical drawing. By using the ratio of T_{50}/L, the designer can predict the level of comfort with a single rating number: ADPI. ADPI can provide further information about the comfort level in a space for results obtained from the NC and mapping selection methods.

Air Distribution Performance Index (ADPI). The air distribution performance index was developed as a way to quantify the comfort level for a space conditioned by a mixed air system in cooling. ADPI uses the effective draft temperature collected at an array of points taken within the occupied zone to predict comfort. ADPI is the percentage of points in a space where the effective draft temperature is between –3 and +2°F and the air velocity is less than 70 fpm. A high percentage of people have been found to be comfortable in cooling applications for office-type occupations where these conditions are met. High ADPI values generally correlate to high space thermal comfort levels with the maximum obtainable value of 100. Select outlets to provide a minimum ADPI value of 80.

The effective draft temperature provides a quantifiable indication of comfort at a discrete point in a space by combining the physiological effects of air temperature and air motion on a human body. The effective draft temperature t_{ed} (the difference in temperature between any point in the occupied zone and the control condition) can be calculated using the following equation proposed by Rydberg and Norback (1949) and modified by Straub (Straub et al. 1956; Straub and Chen 1957) in discussion of a paper by Koestel and Tuve (1955):

$$t_{ed} = (t_x - t_c) - 0.07(V_x - 30) \qquad (2)$$

where

t_{ed} = effective draft temperature, °F
t_x = local airstream dry-bulb temperature, °F
t_c = average (control) room dry-bulb temperature, °F
V_x = local airstream centerline velocity, fpm

T_{50}/L *Selection Method.* This method uses the ratio of cataloged isothermal throw data at 50 fpm to the characteristic length for a given device (Table 3).

Each type of diffuser has different performance characteristics and therefore may provide a different ADPI value for the same cooling application at the same conditions. Calculating T_{50}/L for a given outlet can predict the level of cooling comfort for a space. Using Table 4, the designer can optimize not only the type of diffuser to select but also the size and capacity.

Using T_{50}/L helps designers maximize space cooling comfort; however, this method is not meant to, nor may it be practical to, evaluate T_{50}/L values for each outlet on a project.

Design Procedures. T_{50}/L can be used as a general tool to evaluate cooling comfort levels in a space, at the beginning of design to optimize outlet selection (as shown in the following steps), or at the

end of the process to predict cooling comfort levels in spaces designed using NC and mapping methods:

1. Determine air volumetric flow requirements based on load and room size. For VAV systems, evaluation should include both minimum occupied and maximum design flow rates.
2. Select tentative diffuser type and location in room.
3. Determine room's characteristic length L (Table 3).
4. Select recommended T_{50}/L (or T_{100}/L) ratio from Table 4.
5. Calculate throw distance T_{50} by multiplying recommended T_{50}/L (T_{100}/L for linear slots) ratio from Table 4 by available length L.
6. Locate appropriate outlet size from manufacturer's catalog.
7. Ensure that this outlet meets other imposed specifications (e.g., noise, static pressure loss).

Example 1. For a 20 by 12 ft room, with 9 ft ceiling, with uniform loading of 10 Btu/h·ft^2 or 2400 Btu/h, and air volumetric flow of 1 cfm/ft^2 or 240 cfm for one outlet, find the size for a high sidewall grille located at the center of 12 ft end wall, 9 in. from ceiling.

Table 3   Characteristic Room Length for Several Diffusers (Measured from Center of Air Outlet)

Diffuser Type	Characteristic Length L
High sidewall grille	Distance to wall perpendicular to jet
Circular ceiling diffuser	Distance to closest wall or intersecting air jet
Sill grille	Length of room in direction of jet flow
Ceiling slot diffuser	Distance to wall or midplane between outlets
Light troffer diffusers	Distance to midplane between outlets plus distance from ceiling to top of occupied zone
Perforated, louvered ceiling diffusers	Distance to wall or midplane between outlets

Table 4   Air Diffusion Performance Index (ADPI) Selection Guide

Terminal Device	Room Load, Btu/h·ft^2	T_{50}/L for Maximum ADPI	Maximum ADPI	For ADPI Greater Than	Range of T_{50}/L
High sidewall grilles	80	1.8	68	—	—
	60	1.8	72	70	1.5 to 2.2
	40	1.6	78	70	1.2 to 2.3
	20	1.5	85	80	1.0 to 1.9
Circular ceiling diffusers	80	0.8	76	70	0.7 to 1.3
	60	0.8	83	80	0.7 to 1.2
	40	0.8	88	80	0.5 to 1.5
	20	0.8	93	90	0.7 to 1.3
Sill grille, straight vanes	80	1.7	61	60	1.5 to 1.7
	60	1.7	72	70	1.4 to 1.7
	40	1.3	86	80	1.2 to 1.8
	20	0.9	95	90	0.8 to 1.3
Sill grille, spread vanes	80	0.7	94	90	0.6 to 1.5
	60	0.7	94	80	0.6 to 1.7
	40	0.7	94	—	—
	20	0.7	94	—	—
Ceiling slot diffusers (for T_{100}/L)	80	0.3	85	80	0.3 to 0.7
	60	0.3	88	80	0.3 to 0.8
	40	0.3	91	80	0.3 to 1.1
	20	0.3	92	80	0.3 to 1.5
Light troffer diffusers	60	2.5	86	80	<3.8
	40	1.0	92	90	<3.0
	20	1.0	95	90	<4.5
Perforated, louvered ceiling diffusers	11 to 50	2.0	96	90	1.4 to 2.7
				80	1.0 to 3.4

Solution:
   Characteristic length L = 20 ft (length of room: Table 3)
   Recommended T_{50}/L = 1.5 (Table 4)
   Throw to 50 fpm T_{50} = 1.5 × 20 = 30 ft
   Refer to the manufacturer's catalog for a size that gives this isothermal throw to 50 fpm. One manufacturer recommends the following sizes, when vanes are straight, discharging at 240 cfm: 16 by 4 in., 12 by 5 in., or 10 by 6 in.

More information on conventional mixing systems, and many more design examples, can be found in Rock and Zhu (2002).

FULLY STRATIFIED AIR DISTRIBUTION

Systems that discharge cool air at low sidewall or floor locations with very little entrainment of (and thus mixing with) room air create (vertical) thermal stratification throughout the space. These **displacement ventilation** systems have been popular in northern Europe for some time. Floor-based outlets in underfloor applications may also be used to provide fully stratified air distribution.

Principles of Operation

Thermal displacement ventilation (TDV) systems (Figure 3) use very low discharge velocities, typically 50 to 70 fpm, to deliver cool supply air to the space. The discharge temperature of the supply air is generally above 60°F, although lower temperatures may be used in industrial applications, exercise or sports facilities, and transient areas. The cool air is negatively buoyant compared to ambient air and drops to the floor after discharge. It then spreads across the lower level of the space.

As convective heat sources (Figure 3) in the space transfer heat to the cooler air around them, natural convection currents form and rise along the heat transfer boundary. Without significant room air movement, these currents rise to form a convective heat plume around and above the heat source. As the plume rises, it expands by entraining surrounding air. Its growth and ascent are proportional to the heat source's size and intensity and temperature of ambient air above it. Ambient air from below and around the heat source fills the void created by the rising plume. If the heat source is near the floor (e.g., an occupant), the plume entrains cool, conditioned air from the floor level, which is drawn to the respiration level, and serves as the source of inhaled air. Exhaled air rises with the escaping heat plume, because it is warmer and more humid than the ambient air. Convective heat from sources located above the occupied zone has little effect on occupied-zone air temperature.

At a certain height, where plume temperature equals ambient temperature, the plume disintegrates and spills horizontally. Two distinct zones are thus formed in the room: a lower occupied zone with little or no recirculation flow (close to displacement flow), and an upper zone with recirculation flow. The boundary between these two zones is called **shift zone**. The shift zone height is calculated as the height
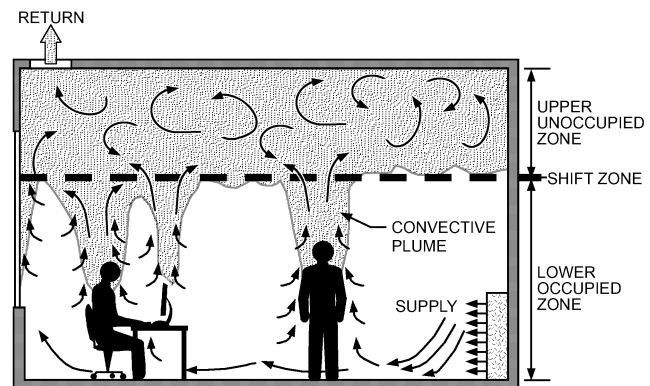
Fig. 3   Displacement Ventilation System Characteristics
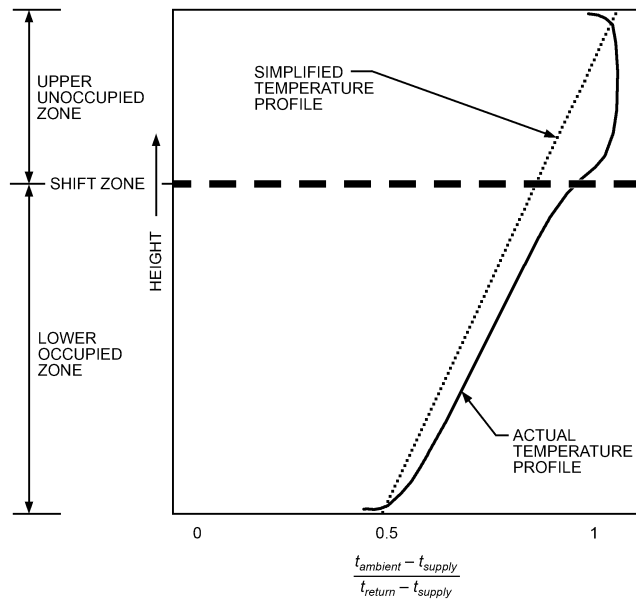
Fig. 4 Temperature Profile of Displacement Ventilation System

above the floor where the total amount of air carried in convective plumes above heat sources equals the supply airflow distributed through displacement diffusers. Actual and simplified representations of the temperature gradient in the space are shown in Figure 4.

Thermal displacement ventilation systems can be modeled as shown in Figure 4. A thin layer of conditioned supply air lies adjacent to the floor. Next is a lower zone in which both ambient temperature and contaminant concentration levels increase with height. Finally, a pool of warm used or contaminated air (the upper zone) may form next to the ceiling, depending on the supplied airflow rate in proportion to the volume of thermal plumes rising through the space.

Space Ventilation and Contaminant Removal

Thermal displacement ventilation is very effective at removing airborne contaminants that are equal to or lighter than the ambient air (e.g., respiratory-produced contaminants, tobacco smoke). According to ASHRAE *Standard* 62.1-2004, these systems have zone air distribution effectiveness E_Z values of 1.2, compared to maximum values of 1.0 for mixed air systems.

Typical Applications

Thermal displacement ventilation systems typically have higher return air temperatures than mixed systems. Thus, they may allow extended periods of air- or water-side economizer operation, especially in mild, relatively dry climates.

Thermal displacement ventilation systems are commonly used in applications such as

- Restaurants
- Casinos
- Large open-plan offices, classrooms, lecture halls, and meeting rooms
- Theaters and auditoriums
- Hospitals and clean rooms
- Other spaces with high ceilings

Benefits and Limitations

Benefits of displacement ventilation systems include the following:

- Removal of airborne contaminants is more effective.

- In mild climates, significantly less energy may be used to maintain the same space occupied zone air temperature in cooling mode.
- Air distribution effectiveness is high: less outside air is required to meet ASHRAE *Standard* 62.1-2004 requirements.
- Diffuser noise level is lower.
- Lower turbulence intensity can reduce draft-related complaints.

Some applications do not favor use of thermal displacement ventilation. Small offices, especially with perimeter exposures, often do not have room for the large outlets that may be required. The following types of areas may be better served by a mixed system:

- Spaces with ceiling heights less than 9 ft
- Spaces with exceptionally high occupied zone heat loads (Bauman and Daly 2003)
- Spaces with ceiling heights below 10 ft that are subjected to significant room air disturbances
- Applications where contaminants are heavier and/or colder than ambient air

When thermal displacement systems are used in humid climates, it may be necessary to dehumidify and possibly reheat supply air to maintain desired space conditions. As with all HVAC air systems' design, a psychrometric analysis is advised.

Outlet Characteristics

Displacement outlets are designed for average face velocities between 50 and 70 fpm, and are typically in a low sidewall or floor location. Return or exhaust air intakes should always be located above the occupied zone for human thermal comfort applications.

Displacement outlets are available in a number of configurations and sizes. Some models are designed to fit in corners or along sidewalls, or stand freely as columns. It is important to consider the degree of flow equalization the outlet achieves, because use of the entire outlet surface for air discharge is paramount to minimizing clear zones and maintaining acceptable temperatures at the lower levels of the space.

Stationary occupants should not be subjected to discharge velocities exceeding about 40 fpm because air at the ankle level within this velocity envelope tends to be quite cool. As such, most outlet manufacturers define a **clear zone** in which location of stationary, low-activity occupants is strongly discouraged, but transient occupancy, such as in corridors or aisles, is possible. Occupants with high activity levels may also find the clear zone acceptable.

Space Temperature Gradients and Airflow Rates

Figure 5 illustrates thermal temperature gradients that might be expected for a classroom with a 10 ft ceiling, served by thermal displacement ventilation. If loads are typical to the application and proper space airflow is supplied, Skistad et al. (2002) indicate that approximately 50% of the total temperature difference between supply air and return or exhaust air is dissipated in clear zone(s) next to the outlet(s). The other half of the temperature gradient is the **space temperature gradient (STG)**, assumed to be linear with air temperature, increasing gradually from floor to ceiling.

For stationary, low-activity occupants, keep supply air temperatures above 60°F. When occupants are very near outlets (e.g., in underseat delivery), keep supply air temperatures at or above 64°F.

Methods of Evaluation

Unlike mixed systems, outlets in thermal displacement systems discharge air at very low velocities, resulting in very little mixing. As such, design of these systems primarily involves determining a supply airflow rate to manage the thermal gradients in the space in accordance with ASHRAE comfort guidelines. ASHRAE *Standard* 55 recommends that the vertical temperature difference between the ankle and head levels of space occupants be limited to no more than 5.4°F to maintain a high degree (>95%) of occupant satisfaction.
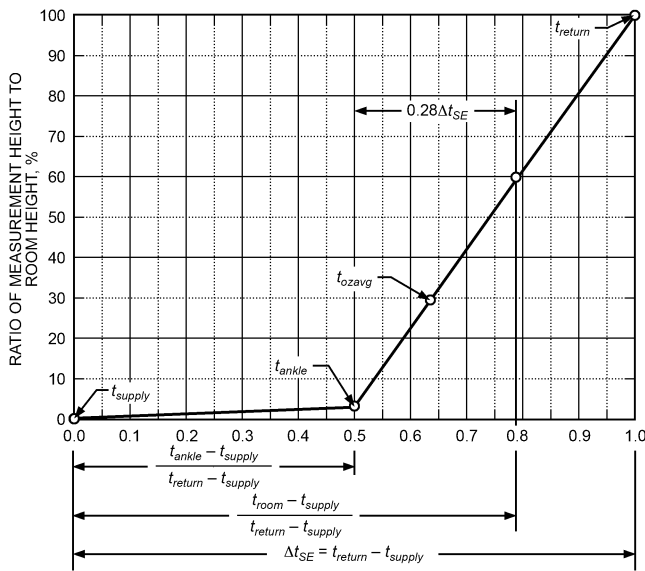
Fig. 5   Temperature Gradient Relationships for Thermal Displacement Ventilation System in Typical Classroom or Office with 10 ft Ceiling

Design Procedures

Displacement ventilation system design is somewhat different than for mixing ventilation. For mixing ventilation systems, where air is mixed relatively evenly throughout the space, the return/ exhaust air temperature is assumed to equal the space temperature. In displacement ventilation systems, the space is divided into two vertical zones. The desired space air temperature is maintained only in the lower zone and is always higher in the upper zone because of the temperature stratification created by natural convection.

Depending on space requirements, two types of design methods are used. The most common is temperature-based, and is used when heat removal is the main objective of the air-conditioning system design (e.g., in schools, offices, auditoriums, sport facilities). The other, the shift-zone method, is used when contaminant removal should be considered (e.g., smoking rooms and other facilities with emissions of gaseous, equal- or lighter-than-air contaminants). The objective of the temperature-based method is satisfying thermal comfort in the occupied zone; the shift-zone design addresses this concern and also ensures that contaminants rise above the occupants' breathing level.

Space temperature gradient (STG) is affected by the strength and location of heat sources in the space, heat exchange by radiation between surfaces in the space, and supply airflow. The design procedure presented in this section is based on Skistad et al.'s (2002) simplified method of estimating temperature gradient (Figure 5). This method is applicable for typical spaces with a ceiling height up to 12 ft, such as classrooms, office spaces, and meeting rooms. When designing more complex spaces, computational fluid dynamics (CFD) software programs may be used (see Chapter 34 of the 2005 *ASHRAE Handbook—Fundamentals* for more information).

The thermal gradient relationships illustrated in Figure 5 can be used to establish an acceptable supply-to-return air temperature differential Δt_{SR} from which the supply airflow rate is calculated. Because the space temperature gradient is assumed to be linear, the occupied gradient in the occupied zone is proportional to the volume of the space it represents. For example, if return height is 10 ft and the occupied zone is 5 ft high, its gradient comprises 50% of the space temperature gradient, or 25% of Δt_{SR}. The temperature difference between room air at the top of the occupied zone and the supply air is therefore 75% of Δt_{SR}.

Determining an acceptable Δt_{SR} should consider both the room-to-supply temperature differential and the occupied zone temperature gradient (as limited to 5.4°F by ASHRAE *Standard* 55).

In general, high-ceiling applications allow larger supply-to-return air temperature differentials, because the occupied zone is a smaller percentage of total room air volume. However, the differential may be reduced by limitations on the supply air temperature, as shown in Example 2.

The supply airflow rate Q to achieve Δt_{SR} is calculated from Equation (1).

Example 2. A classroom with a 10 ft ceiling is to be cooled by thermal displacement ventilation. The supply air temperature is 62°F and room temperature is maintained at 76°F at 5 ft level. The total sensible heat gain of the space is 28,000 Btu/h.

Calculate the (1) overall temperature differential between supply and return airflow and (2) required space airflow. Identify return air temperature and temperature at occupants' ankle level.

Solution: Using the relationships in Figure 5, the supply-to-return temperature differential Δt_{SR} and return air temperature can be predicted as follows:

$$\Delta t_{SR} = (t_{room} - t_{supply})/0.75 = (76 - 62)/0.75 = 18.7°F$$

$$t_{return} = t_{supply} + \Delta t_{SR} = 62 + 18.7 = 80.7°F$$

To ensure a high level of thermal comfort, the occupied-zone temperature gradient Δt_{oz} should not exceed 5.4°F. For this application, the occupied zone gradient is acceptable:

$$\Delta t_{oz} = \Delta t_{SR} \times 0.25 = 18.7 \times 0.25 = 4.7°F$$

From Equation (1), the airflow required to maintain this gradient is

$$Q = 28,000/(1.08 \times 18.7) = 1386 \text{ cfm}$$

Application Considerations

Displacement ventilation is a cooling-only method of room air distribution. For heating, a separate system is generally recommended. Displacement ventilation can be used successfully in combination with radiators and convectors installed at the exterior walls to offset space heat losses. Radiant heating panels and heated floors also can also be used with displacement ventilation. To maintain displacement ventilation, outlets should supply ventilation air about 4°F lower than the desired room temperature.

Thermal displacement ventilation systems can be either constant or variable air volume. A thermostat in a representative location in the space or return plenum should determine the delivered air volume or temperature. If the time-averaged requirements of ASHRAE *Standard* 62.1-2004 are met, intermittent on/off airflow control can be used.

Avoid using thermal displacement and mixed air systems in the same space, because mixing destroys the natural stratification that drives the thermal displacement ventilation system. Thermal displacement systems can be complemented by hydronic systems such as chilled floors. Use caution when combining chilled ceilings, beams, or panels with fully stratified systems, because cold surfaces in the upper zone of the space may recirculate contaminants stratified in the upper zone back into the occupied zone.

Chen and Glicksman (2003) provide additional information on fully stratified air distribution systems.

PARTIALLY MIXED AIR DISTRIBUTION

A partially mixed system's characteristics fall between a fully mixed system and a fully stratified system. It includes both a high-velocity mixed air zone and a low-velocity stratified zone where room air motion is caused by thermal forces. For example, floor-based outlets, when operating in a cooling mode with relatively high discharge velocities (>150 fpm), create mixing, thus affecting the amount of stratification in the lower portions of the room. In the

upper portions of the room, away from the influence of floor outlets, room air often remains thermally stratified in much the same way as displacement ventilation systems.

Principles of Operation

Supply air is discharged, usually vertically, at relatively high velocities and entrains room air in a similar fashion to outlets used in mixed air systems. This entrainment, as shown in Figure 6, reduces the temperature and velocity differentials between supply and ambient room air. This discharge results in a vertical plume that rises until its velocity is reduced to about 50 fpm. At this point, its kinetic energy is insufficient to entrain much more room air, so mixing stops. Because air in the plume is still cooler than the surrounding air, the supply air spreads horizontally across the space, where it is entrained by rising thermal plumes generated by nearby heat sources.

Research and experience have shown that the amount of room air stratification varies depending on design, commissioning, and operation. Control of stratification includes the following considerations:

- By reducing airflow and mixing in the occupied zone, fan energy can be reduced and stratification can be increased, approaching a reasonable target at 3 to 4°F temperature difference from head to ankle height, which satisfies ASHRAE *Standard* 55-2004.
- By increasing airflow and mixing in the occupied zone, excessive stratification can be avoided, thereby improving thermal comfort.

In practice, successful installation requires an optimal balance of these issues (Webster and Bauman 2006).

Figure 6 shows one example of the resulting room air distribution in which the room air is mixed in the **lower mixed zone**, which is bounded by the floor and the elevation (**throw height**) at which the 50 fpm terminal velocity occurs. At this elevation, stratification begins to occur and a linear temperature gradient, similar to that found in thermal displacement systems, forms and extends through the **stratified zone**. As with thermal displacement ventilation, convective heat plumes from space heat sources draw conditioned air from the lower (mixed) level through the stratified zone and to the overhead return location. A third zone, referred to as the **upper mixed zone**, may exist where the volume of rising heat plumes terminate. Although velocities in this area are quite low, the air tends to be mixed.

Space Ventilation and Contaminant Removal

Partially mixed systems' ventilation and contaminant removal efficiencies vary considerably. Restricting mixed conditions to below the breathing level results in most respiratory-associated contaminants being conveyed directly to the overhead return by heat plumes rising from occupants. If the lower mixed zone extends above the breathing level, contaminants are entrained and horizontally transmitted across occupied levels of the space, as occurs in mixed air (dilution ventilation) systems.
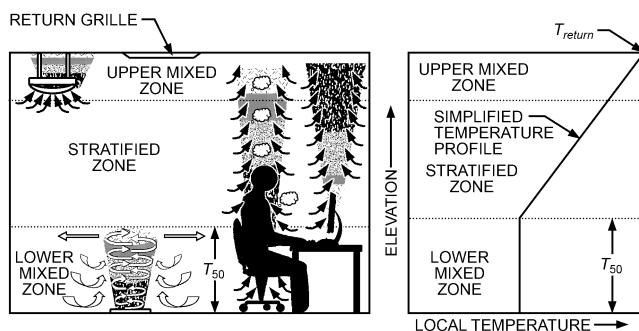
Fig. 6   UFAD System in Partially Stratified Application

According to ASHRAE *Standard* 62.1, these systems may have zone air distribution effectiveness E_Z values that exceed those of fully mixed systems.

Typical Applications

Partially mixed systems are commonly used in applications such as the following:

- Office buildings with raised floors
- Call centers
- Libraries
- Casinos
- Other spaces with open or high ceilings

Many underfloor air distribution (UFAD) systems can be classified as partially mixed systems. These systems are popular because of their relocation flexibility when used in conjunction with raised-access flooring systems. Outlet accessibility also allows easy occupant adjustment of space airflow delivery. The cavity beneath the access floor tiles is generally pressurized and used as a supply air plenum. Supply outlets placed in access floor tiles are commonly tapped directly into the pressurized plenum, but may be ducted from a fan-assisted terminal unit mounted beneath the floor.

Benefits and Limitations

Benefits of UFAD systems include the following:

- Using a raised floor system may substantially reduce air distribution ductwork and terminal requirements.
- Central fan energy consumption may be lower.
- The space service flexibility of the access floor platform is extended to include HVAC services as well. Nonducted outlets can be easily added or relocated.
- Because most outlets are sized to handle loads typical to an interior single-occupant office or workstation, they can be placed within the workstation to give occupants thermal control over their individual work environment. This makes higher individual occupant comfort levels possible.
- Air- and water-side economizer opportunities are extended, especially in mild and relatively dry climates.

Applications where contaminants are heavier and/or colder than ambient air may be better served by a mixed air system. As with thermal displacement systems, partially stratified systems in humid climates require that the outside air be sufficiently dehumidified to satisfy space latent requirements. The temperature of dehumidified air must often be increased before introduction to the occupied space.

Outlet Characteristics

One outlet type is a swirl diffuser with a high-induction core, which induces large amounts of room air to quickly reduce supply to ambient air velocity and temperature differentials. Supply air is injected into the room as a swirling vertical plume close to the outlet. Properly selected, these outlets produce a limited vertical projection of the supply air plume, restricting mixing to the lower portions of the space. Most of these outlets allow occupants to adjust the outlet airflow rate easily. Other versions incorporate automatically controlled dampers that are repositioned by a signal from the space thermostat and/or central control system.

Another category includes more conventional floor grilles designed for directional discharge of supplied airflow. These grilles may be either linear or modular in design, and may allow occupants to adjust the discharge air pattern by repositioning the core of the outlet. Most floor grilles include an integral actuated damper, or other means, that automatically throttles the volume of air in response to the zone conditioning requirements.

Room air induction allows UFAD diffusers to comfortably deliver supply air a few degrees cooler than possible with outlets

used for thermal displacement ventilation outlets. The observance of clear, or adjacent, zones above and around the diffusers, where stationary occupants should not reside, is recommended. Outlet manufacturers typically identify such restrictive areas in their product literature.

Space Temperature Gradients and Airflow Rates

The objective of partially mixed systems is to condition the air in the occupied zone while allowing stratification to naturally occur. By allowing this stratification, some of the space heat gain can be removed by return or exhaust instead of by supply air delivery to the space. If the supply airflow rate and sensible heat gains affecting the lower zone are balanced, an acceptable temperature gradient (<5°F) can be achieved in the occupied zone. Supply airflow beyond that required by these heat gains reduces the degree of stratification shown in Figure 6. If the supply airflow rate is insufficient, excessive vertical space temperature gradients may occur.

Accurate calculation of the space design supply airflow rate requires analysis of all space sensible heat gains to determine their contribution to the lower zone. Although there is not yet a single recognized procedure for calculating these airflow rates, most UFAD equipment manufacturers offer guidance.

Methods of Evaluation

As for thermal displacement systems, design involves determining a supply airflow rate that limits thermal gradients in the occupied zone in accordance with ASHRAE *Standard* 55 guidelines. ASHRAE *Standard* 55 recommends that the vertical temperature difference between the ankle and head level of space occupants be limited to no more than 5.4°F if a high degree (>95%) of occupant comfort is to be maintained.

Design Procedures

The design of partially mixed air distribution systems requires identifying both thermal and contaminant removal objectives:

- The desired space temperature, the elevation to which it applies, and an appropriate supply air temperature must be identified.
- The supply air temperature for UFAD systems served by a pressurized or neutral pressure floor plenum should be limited to that which results in a relative humidity level below 80% in the floor cavity, to minimize the threat of mold or fungus growth.
- Supply air temperatures tend to rise as air moves through the floor cavity; therefore, the supply air temperature varies with its distance traveled. When determining space airflow requirements, supply temperatures should be modified accordingly to avoid undercooling the occupied space. Bauman and Daly (2003) discuss this subject further.
- If the objective is to provide displacement ventilation of respiratory contaminants in the stratified zone, mixing must be limited to below the breathing level of most space occupants.
- Outlets should be located far enough from stationary occupants to ensure that they are not subjected to drafts that might cause thermal discomfort. Outlet manufacturers generally prescribe clear zones that quantify this separation distance.

Application Considerations

ASHRAE's *Underfloor Air Distribution Design Guide* (Bauman and Daly 2003) includes a thorough discussion of issues involved in the design, application, and commissioning of UFAD systems. Some considerations include the following:

- Supply temperatures in the access floor cavity should be kept at 60°F or above, to minimize the risk of condensation and subsequent mold growth.

- Most UFAD outlets can be adjusted automatically by a space thermostat or other control system, or manually by the occupant. In the latter case, outlets should be located within the workstation they serve.
- Use of manually adjusted outlets should be restricted to open office areas where cooling loads do not tend to vary considerably or frequently. Perimeter areas and conference rooms require automatic control of supply air temperatures and/or flow rates because their thermal loads are highly transient.
- Heat transfer to and from the floor slab affects discharge air temperature and should be considered when calculating space airflow requirements. Floor plenums should be well sealed to minimize air leakage, and exterior walls should be well insulated and have good vapor retarders. Night and holiday temperature setbacks should likely be avoided, or at least reduced, to minimize plenum condensation and thermal mass effect problems. With air-side economizers, using enthalpy control rather than dry-bulb control can help reduce hours of admitting high moisture-content air, thus also reducing the potential for condensation in the floor plenums.
- Avoid using stratified and mixed air systems in the same space, because mixing destroys the natural stratification that drives the stratified system.
- Return static pressure drop should be relatively equal throughout the spaces being served by a common UFAD plenum. This reduces the chance of unequal pressurization in the UFAD plenum.

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CHAPTER 57

INTEGRATED BUILDING DESIGN

INTEGRATED building design (IBD) is a collaborative process of preparing design and construction documents that result in optimized project system solutions. For IBD to succeed and be beneficial to the project, the entire project delivery team must be committed to, understand, and remain engaged and involved in the process from project inception through operation and maintenance.

This chapter provides a working knowledge of IBD, highlights activities that support collaboration, and helps the HVAC design professional develop a structured and integrated approach to project delivery. The basic process framework is outlined, and major milestones are identified.

The resources in the References and Bibliography, as well as other Handbook chapters and ASHRAE guidelines and standards offer in-depth guidance on various IBD application requirements and should be referred to for more information.

PROJECT DELIVERY

Delivery of solutions in the built world is accomplished in many ways and through various delivery techniques. Whether it is design-bid-build, design-build, design-construction manager (design-CM), etc., each delivery method requires interaction between design professionals representing inclusive elements of the project.

Sequential Design Process

In a sequential design process (SDP), elements of the built solution are defined and developed in a systematic, sequential, and somewhat isolated process. As each element is resolved, a new element is added to build on the overall project solution. A typical SDP can be briefly outlined as follows:

1. The architect develops the building program and proposes a facility layout to support the program.
2. Trade budgets are set to comply with the overall construction budget.
3. The structural engineer defines the skeleton to support the proposed facility.
4. Facility services engineers are given the proposed layout, structural system, and trade budgets, then directed to apply mechanical, electrical, and plumbing (MEP) solutions.
5. Discipline design evolves on individual paths to support the allocated trade budgets.
6. Coordination impacts are shared with the project team.

Integrated Design Process

An integrated design process (IDP) discourages sequential philosophy and promotes holistic collaboration of the project team members during all phases of project delivery. Emphasis is placed

on optimizing system solutions that are responsive to the objectives defined for the project. Optimizing system solutions requires the participation of all team members.

Effort Shift

Execution of the IDP requires a departure from conventional SDP methodology. This change includes a true shift in effort during the classical design phases (schematic design, design development, and construction documents), but also includes the addition of enhanced efforts outside the traditional design phases.

The classical design phases promote a certain level of SDP based on their inherent percentage development model. SDP typically unfolds along the following development path:

1. During the schematic design phase, the basic form and function of the facility are defined to meet the program. Facility services are described in concept to support the developed facility construction.
2. During the design development phase, systems proceed in parallel development paths to find best-fit solutions that meet the project budget and provide compliance with prescribed regulatory requirements such as building, life safety, energy, and ventilation codes. Life-cycle cost activities (LCCA) may be used to optimize individual discipline solutions in response to the schematic design development package.
3. During the construction document phase, all building components are detailed into work results suitable for procurement and construction.

Integrated design alters this traditional delivery model by front-loading collaboration efforts to optimize building system solutions in response to the defined project objectives. Integrated design is most effective when key issues are addressed early in design and planning (see Figure 1). An important point to remember is that implementation of the IDP does not necessarily mean getting more things done early; it means getting the right things done early. To accomplish this, traditional team roles that lagged early design activities must participate on equal footing earlier in the process, so that holistic issues are considered before it becomes too late to effect responsible inclusion.

OBJECTIVES

IDP is accomplished by responding to project objectives. These may be defined by the owner before team selection, or developed by the project team during any project phase. The key is to define substantive objectives that can materialize into practical, constructable results. Prominent objectives are outlined in this section. Definitions of objectives in the IDP are only highlighted here; consult application-specific material when considering the effects of each objective.

The preparation of this chapter is assigned to TC 7.1, Integrated Building Design.
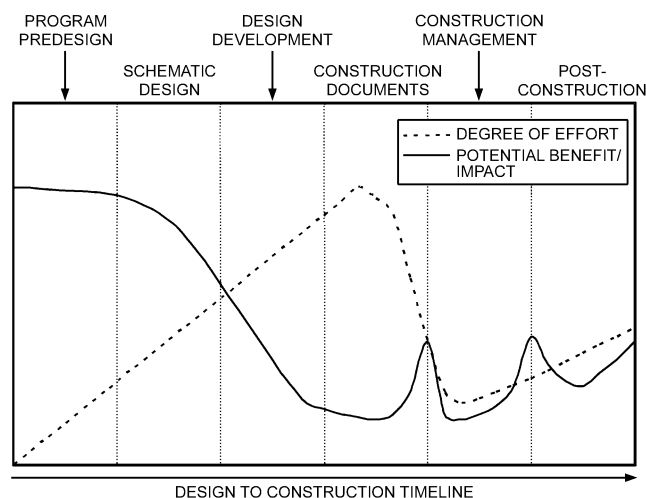
Fig. 1   Benefits of Early Design Collaboration
(Lewis 2004)

Various organizations and owner entities have developed sustainable, green, and high-performance prescriptive point systems to promote select project delivery objectives. Typically, these point structures address sustainable sites, water efficiency, energy and atmosphere, materials and resources, and indoor environmental quality. Although incorporation of these objectives is a highly desirable pursuit and promotes responsible environmental stewardship, the team must realize that desired accumulation of points in a prescriptive rating system should not shift focus from meeting the defined project objectives.

Energy Use

Energy performance objectives can be as simple as providing minimum prescriptive energy code compliance, or as detailed as providing a net-zero-energy performance facility. The extent and complexity of the objectives must be tailored to each individual project. Sample objectives that may be encountered include the following:

- Provide minimum prescriptive compliance per applicable energy code requirements
- Improve energy performance by an owner-defined percentage beyond applicable energy code benchmark(s)
- Provide a facility site energy density of less than owner-defined consumption per unit area
- Provide a facility source energy density of less than owner-defined consumption per unit area
- Provide owner-defined percentage of facility's source energy from renewable resources
- Limit owner-defined percentage of facility's source energy to nonrenewable or consumable resources

Typically, energy-related objectives address consumption, efficiency, and generation (site and source) issues. There are a myriad of variations, combinations, and themes that objectives can take regarding these factors. These combinations serve as an excellent example of why the underlying objectives for the project should be fulfilled before performance-rating-system point tabulation becomes the primary focus.

Indoor Environmental Quality (IEQ)

IEQ objectives vary with the programmed use for the building. Each aspect of IEQ must be considered.

Acoustical comfort may require specific focus because of the nature of activities inside and around the facility. Theaters, for example, have certain prescribed noise criteria that must be

provided to allow for intended operation. Achieving prescribed noise criteria for specific building operations requires knowledgeable collaboration by all parties that control the source noise, transmission paths, and measured point of sound pressure.

Depending on the facility, **thermal comfort** may or may not be a critical objective. The project team needs to clearly understand the individual facility thermal conditions and the range of acceptable variation. This criterion has a significant effect on the size, type, and complexity of potential infrastructure solutions.

Depending on the climate and operational needs, **humidity** or **moisture control** may be an appropriate objective. This objective can be further expanded to address building protection, occupant comfort, or process needs.

Ventilation effectiveness deals with the practical and reliable means of providing ventilation air into the breathing zone of the facility occupants. Table 6-2 in ASHRAE *Standard* 62.1 identifies zone air distribution effectivenesses E_z ranging from 0.5 to 1.2 for various air distribution configurations. An objective that may be defined is to limit HVAC solution configuration to systems that provide an E_z value of 1.0 or greater.

Visual quality can be a concern for certain operations. The quality of ambient light in a space can have direct effect on occupants' productivity. Properly applied and controlled, daylighting can improve the visual quality of the occupied space and reduce the capacity of the HVAC systems by decreasing the need for artificial indoor lighting systems.

Water Usage

Potable water is essential to life and faces continuous pressures relative to availability and quality. IBD objectives for water usage typically focus on conservation and reclamation efforts. Water has a cost associated with its use. This use should be modeled in the total ownership cost of a facility.

Conservation and reclamation of water do not apply only to plumbing systems. HVAC systems can consume significant amounts of water and are prime candidates for environmentally responsible project objectives. Sample objectives that have an HVAC influence include the following:

- Reclaim all cooling condensate discharge for use in gray-water systems. Note that reclaimed gray water can be applied to a host of facility service applications, such as cooling tower makeup, landscape irrigation, urinal flushing, etc.
- Capture all facility storm water drainage for use as gray-water makeup for HVAC, plumbing, and landscaping needs.
- Increase concentration limits and/or decrease cycles on cooling tower blowdown to conserve water consumption. This, of course, must be balanced against the suitability of an integrated maintenance program and limited to local water quality characteristics that contribute to scale, corrosion, fouling, and microbial growth.

Vulnerability

Global events and operational needs may dictate that built solutions address vulnerability objectives. The facility infrastructure may require protection from outside seismic incidents, blast events, or chemical and biological contamination. Inside operations that create explosion, chemical, biological, or radiological hazards may require focus. Additionally, protecting occupants in the facility may be an inclusive or standalone priority. In any case, vulnerability objectives create some challenging opportunities for collaboration and demand that the project team have an effective prioritization system in force on the project. See Chapter 58 for more information on the topic.

Environmental Stewardship

Waste reduction is a pressing need in the built world. The capacity of landfills to absorb construction debris is not limitless. Reuse

and recycling of construction debris can help mitigate landfill overuse. Also, when materials cannot be harvested or obtained from the project site, using new construction materials that include recycled content is a proactive consideration.

As concerns with global warming and greenhouse gases increase, minimizing the carbon footprint of the facility may become a critical objective. This will require a unique collaborative effort to minimize the sum of the embodied energy and carbon emissions of all processes and components required to construct, own, operate, and maintain a facility.

Critical Operations

Certain objectives are critical to operations for data centers, emergency response, law enforcement, government, health care, shelters, manufacturing, and pharmaceutical facilities. For example,

- Facilities that require high reliability must focus on ensuring that systems and components meet the specified probability they will operate for the duration of use. As the required reliability increases, infrastructure design must respond in kind with system redundancy and diversity.
- Facilities that require high availability must focus on ensuring that systems and components meet the specified probability they will operate and be accessible when required for use.
- Scalability may dictate that infrastructure have provisions for expansion and growth relative to dynamic business factors and technology development.

General Operations

Accessibility priorities may dictate that some infrastructure have unique requirements to ensure proper performance and serviceable attention during the operational life. Accessibility has an infrastructure cost effect that must be factored into the total ownership cost.

Replaceability objectives may define where facility infrastructure can be located so that replacements can be made when the useful life has expired. Total ownership solutions should plan for the costs to replace equipment and not leave this as a hidden burden for the facility owner to bear later.

Many owners face a dynamic known as churn (reconfiguring a space or changing its use). Objectives that plan for churn can help mitigate complete replacement of facility services if changes need to be made.

TOOLS

IDP requires detailed simulation and evaluation of system solutions across multiple design responsibilities. Performing these simulations by hand can be onerous. Tools are readily available in the industry to assist the project team in maximizing their collaboration efforts.

This section discusses three critical, fundamental types of tools suggested for use in executing IDP. These are by no means the only tools available; an abundance of tools are available from government, utility, commercial, manufacturing, and technical society sources. Comprehensive listings of potential resources are available on the National Institute of Building Sciences (NIBS) Whole Building Design Guide Web site (http://www.wbdg.org/index.php).

Building Information Modeling

Building information modeling (BIM) is the process of using intelligent graphic and data modeling software to create optimized and integrated building design solutions. As such, it is an enabling tool for IBD (see Figure 2). The ultimate goal of BIM is to assemble a single database of fully integrated and interoperable information that can be used seamlessly and holistically by all members of the design and construction team, and ultimately by owners/operators throughout a facility's life cycle. The desired result is a BIM model where three-dimensional (3D) graphical imaging carries real-time (i.e., immediate and dynamic access) data, and where every line and every object carries real-life intelligent physical and performance data. That model includes the aesthetic, physical, and thermal properties of each component, as well as specification and cost data. The design team interfaces with the model to seamlessly generate comprehensive simulation evaluations, including natural daylight modeling, energy modeling, and life-cycle cost analysis of the building's integrated systems.

The modeling technology can start with direct data transfer from the design calculation software into graphic layouts (for systems such as structural steel, fire protection, or other modular elements). Alternatively, it can use the graphic layouts as direct input to load calculations (e.g., pipe sizing, duct sizing). Modeling programs can also link to specifications and to manufacturers' Web sites for data input. Either way, building information modeling technology already extends into fully integrated 4D modeling (adding the fourth dimension of time for scheduling or sequencing using programs) and 5D modeling (adding the fifth dimension of cost for estimating and budget control).

After design optimization is complete, the original modeling software can compile data from each discipline and generate a set of digital 2D or 3D construction documents for use in procuring construction bids. The model can interface with a contractor's cost estimating, scheduling, and project management software and manufacturers' material, fabrication, and cost databases to generate optimized cost estimates and construction schedules. The development can continue with the provision of automatic bills of material (BOM) and generation of automatic shop drawings for everything from structural steel to sheet metal duct fabrication, fire protection and piping fabrication, electrical cabling and bus duct layouts, etc. As construction progresses, the model can be continually updated to as-built conditions, including integration of manufacturers' installation,
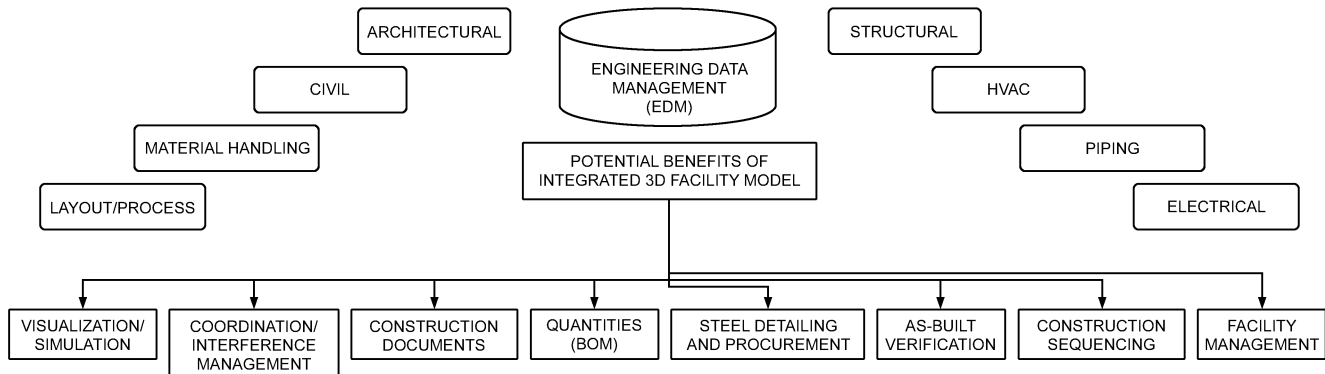
Fig. 2 Overview of BIM Benefits

operation, and maintenance data. This extends all the way through start-up and commissioning, and to facilities management with hyperlinks to operating and maintenance manuals, service contractors, and so forth.

There is a significant amount of work being done worldwide on software tool and protocol developments by governmental agencies, nonprofit and research organizations, as well as commercial entities, to facilitate and promote BIM technology. There is also significant new industry foundation class (IFC) compliant application software under development.

A major key to the success of these efforts is establishing common software protocols. The International Alliance for Interoperability (IAI), a council of NIBS, developed models to address this issue. IAI's Web site (http://www.iai-na.org/index.php) also provides information on programmable eXtensible Markup Language (XML) data models for information transfer between disparate software packages (e.g., aecXML is a framework for using an XML standard specifically related to technology in architecture, engineering, and construction). They also offer comprehensive, intelligent, and universal data models through IFCs to IFC.XML2 (ISO 10303-28), which incorporate HVAC schemas compatible with ifcXML/IFC2X3 code (ISO *Standard* 10303-11), as well as data elements that represent entire portions of a building or system. These are used to assemble computer-readable models of the facility that contain all of the information on the parts and their relationship (ISO/PAS-*Standard* 16739).

NIBS' Facility Information Council is developing a national building information model standard; NIBS' Building Enclosure Technology and Environment Council and the Facility Maintenance and Operations Council are also doing related work. NIBS is working with IAI to develop an overall integrated program developing and expanding IFC component values under the umbrella "buildingSMART," which combines BIM technology with information for the construction (IFC) global ISO standard. The first draft of the Standard is now available for review (IAI 2007).

Energy Modeling

Energy modeling uses scientific methods and analytical tools to estimate the energy consumption patterns of a given facility, constructed of given materials, located in a given climate zone, and operated according to given schedules. These tools and methods range from simple hand calculations and spreadsheets to the most sophisticated software packages designed to consider numerous building configurations, various zoning options, and multiple systems with many varied hours of operation. Some of the more common software tools include programs free for download such as the U.S. Department of Energy's (DOE) DOE2, Energy10, EnergyPlus, and eQuest. Commercial entities and equipment manufacturers also have products available to support building load calculation and detailed energy performance modeling.

Energy modeling should be used to help integrate and optimize a building's energy-consuming systems' performance over the facility's expected life cycle. Successful application of this tool comes from evaluating system solutions as early as possible to develop best-fit solutions for the developing design, thus minimizing radical design changes late in the design phases.

Energy modeling may also be used if it becomes necessary to value-engineer a project after the design phase is complete. Simple substitutions of less costly materials, products, equipment, or systems during the value-engineering stage of a highly integrated building design may have serious and profound negative effects on the building's future energy and environmental performance if not properly analyzed before acceptance.

Energy models should only be developed by team members who have extensive experience in the creation of such models and who truly understand the dynamics of building operations. Energy modeling is a tool used to estimate the energy performance of a building

and its systems for comparison to other alternatives performing under similar conditions and constraints at a given time, and is used for informed and intelligent decision-making purposes. Weather patterns change; plug loads and technology use change; users' preference for thermostat set points often differ from those modeled; material properties change and degrade over time; system and equipment maintenance may be kept current or deferred after owner occupancy; and hours of usage and operation change; these are just a few reasons why modeled energy use rarely tracks favorably with actual usage patterns. The following points should always be kept in mind when using energy models for system evaluation:

- Model results are not a guarantee of actual or future performance
- Model results are not a guarantee of actual or future energy costs

Refer to Chapter 32 in the 2005 *ASHRAE Handbook—Fundamentals* for an in-depth discussion on modeling methods for systems design and design optimization.

Life-Cycle Analysis Tools

All system evaluations share a common need to demonstrate what the financial effects are relative to total ownership cost. This requires a comprehensive comparison of capital, utility, energy, maintenance, replacement, disposal, and occupant costs for the facility's projected life. Life-cycle cost analysis (LCCA) provides a means of examining how each of these factors impact the owner's cost obligations.

A comprehensive methodology for facilitating life-cycle comparisons can be found in the National Institute of Standards and Technology's *Handbook* 135, Life-Cycle Costing Manual for the Federal Energy Management Program (NIST 1996). NIST provides a number of supplemental publications and tools that should be used in conjunction with this source, including the following:

- Annual supplements to *Handbook* 135, providing annually updated energy price indices and discount factor multipliers
- The DOE's Building Life-Cycle Cost (BLLC) Computer Program, which provides an electronic means of applying the methodology of *Handbook* 135

All of NIST's life-cycle publications, tools, and annual updates may be downloaded from the U.S. Department of Energy's Federal Energy Management Program Web site.

Chapter 36 in the 2003 *ASHRAE Handbook—HVAC Applications* contains expanded LCCA reference material that focuses on direct HVAC system and component effects, as well as valuable perspectives and data on owning, operating, and maintenance cost factors.

CLIENT PROCESS

Project inception begins with the owner and a need to begin construction of a facility. Successful incorporation of IBD objectives is set at this point, before execution of the first design calculation.

Programming

When a need for facility space is created, the owner must first evaluate options available to meet the required facility need. The scenarios of construction, reduced construction, or no construction should be debated to determine which option provides the best-fit alternative. Questions to consider include the following:

- Are adaptive reuse alternatives available?
- Does the program need have redundancies that contribute to wasteful infrastructure construction?
- Can operating schedules be adjusted to minimize built space?
- Do consolidation opportunities exist within and outside the organization that could foster more environmentally responsive built solutions?

- Do multiple use opportunities exist that can support additional program uses, expanded use potential, and operational scalability?
- What are the real and artificially generated work sequence needs? Accelerated project delivery may be required, but such action may not allow for optimized solutions to be thoroughly developed and evaluated.
- What are the project objectives as seen from the owner's perspective? Early definition of objectives is instrumental in assembling the correct project team members.
- Based on definition of the project objectives, who will best serve the role as IBD champion for the owner's interest?

Siting

The location of the proposed built facility directly influences the course the IDP takes. Site alternatives need to be researched to determine whether site contamination may influence infrastructure solutions, or whether wetland offset measures need to be implemented at other sites.

The location and suitability of utility resources must be identified. Sites should be selected that allow options and flexibility when system solutions are being considered. Lack of available utilities affects optimization models. Basic features to consider include the following:

- Is potable water available from a municipal source, or will well water be required? If provided from a municipal source, what line pressures are available?
- Is a municipal sanitary sewer available, or will an on-site septic system be required?
- What is the proximity of electricity, gas, and district energy systems?
- Is the site conducive to implementation of renewable site/source energy?

Neighbor relations present another decision matrix for the owner to consider. The proposed location of a built facility and the specific operational dynamics may contribute negatively to the surrounding community. Questions to ask that may lead to unique project mitigation objectives include the following:

- What will the effects on traffic be for building occupants and neighboring communities?
- Do operational usage schedules complement neighboring communities?
- Will light-trespass mitigation and ambient-noise abatement be required?

Budgeting

Once the owner's program is set, siting options have been evaluated, and mitigation needs have been defined, the owner needs to appropriate funding to support design, construction, and operation of the facility. Funding sources should be planned to cover anticipated professional services fees, capital construction costs, contingencies, escalation costs, maintenance costs, utility/energy costs, and occupant costs. Allocations should be made with an eye towards encouraging collaborative optimization efforts and leveraging noncapital costs to minimize overall total ownership cost.

Team Selection

Design team members should have a high degree of competence and knowledge gained though education and experience on similar projects. When team selection occurs can vary, depending on the client's in-house capabilities. Typically, the design team needs to assist the owner during initial programming and siting activities. Regardless of the timing, it is imperative that the team be selected based on qualifications that support the project objectives.

COLLABORATION

Collaborative design requires that all members of the design team possess demonstrated expertise, an ability to work collectively in a nonisolated setting, and a drive of stewardship to support the IDP vision. Team members should share similar corporate philosophies, have compatible operating procedures, use common optimization tools, and be committed to adhering to consistent interdisciplinary quality assurance/quality control (QA/QC) procedures.

Teamwork

Working with a team requires that participants engage in joint decision making. Individual thinking and processes must give way to support the team and a decision-making mentality that supports the direction of the team. Individuals must keep in mind that their actions and reactions affect integrated system solutions. Design in isolation does not support team collaboration.

Team members must foster a professional level of respect for each other. When individuals suggest new strategies to improve the whole, dissident views will occur. Emotions must be removed from these events. Evaluations must be made on objective application and support of meeting project objectives.

The project team leader should be trained to handle conflict management and dissident views in a professional manner. Consensus agreement will not always be apparent, and the project team must avoid fracture of the collaborative effort when differences occur.

Effective, concise, and complete communication must be adopted to keep the team informed of all decisions across all design disciplines. Communications within the project team should be standardized as much as possible. Each form of communication should contain the date the communication originated, any revision dates, project name, project number, and the originator's contact information. In addition, a clear and concise subject line should be included to focus recipients to the subject matter at hand. For collaboration to work, all team members must be kept in the communication loop so that each understands where the collaboration process stands.

Team Formation

The importance of experience in an integrated design team cannot be stressed enough. Systems thinking requires input from individuals who have extensive design experience and understand how systems and components interact. IDP cannot succeed when key representatives are cast into on-the-job training. On the other hand, IDP provides an excellent opportunity to mentor and train supporting staff in system integration, and the opportunity should be fully exploited.

Participation in IDP requires individuals to have a proactive attitude that supports the ups and downs of iterative system evaluation. Individuals who can see the big picture and appreciate that the whole will be better than the sum of the parts enhance the team efforts.

Participants should have experience with optimization techniques. This equates to more than being able to run a load calculation. True optimization expertise requires understanding how building systems interact, what elements can be examined for the benefit of the whole, and how to evaluate results in detailed financial models that consider all ownership costs.

Some projects may require adding specialty consultants to the project team to support activities such as smoke control, acoustics, seismic restraint, or food service. Rarely do all expertise needs reside within the same firm on complex projects. Managing outside specialty consultants is an added responsibility that must be factored into the collaborative process.

As with the owner, the design team requires an IBD champion to keep focus on the project objectives.

Decision-Making Criteria

As system evaluations are made, benchmarks or baselines must be established to measure the suitability of system evolution. These

decision-making criteria must be agreed to with the owner before any design work begins. Criteria need to be realistic, allow for maintaining pace with the budget limitations, accommodate strategic flexibility, and address budget correction possibilities when the need arises. The basis of the criteria depends totally on the owner's resource capabilities and financial position, but in all cases should be based on meaningful life-cycle analysis.

Scenarios may arise that challenge the design criteria and defined objectives for the project. It is not uncommon for project scopes or financial factors to change during project design, procurement, or construction. This deviation from the original path may require a reprioritization of objectives and a change in the decision-making criteria. The team should be prepared to adapt to such dynamics and be able to refocus the IDP in a responsive and efficient manner.

Strategy Development

To proceed with the IDP, proposed strategies should lead the team toward a built facility of integrated systems. Development of these strategies is influenced by the prioritization of project objectives and by the direction of the developing building solution. Using the simple, but not quantified, objective of reduced energy use as an example, the following broad strategies and substrategies reflect the progressive optimization for a commercial office building in the southeastern United States. Note that the example does not provide an all-inclusive strategy roadmap, or represent a fixed recommendation.

1. Minimize building envelope load
   - Optimize siting and footprint aspect ratio to maximize east/west orientation
   - Incorporate effects of major sky obstructions such as buildings, trees, and geological features
   - Minimize east/west-facing glass
   - Incorporate overhangs to reduce solar radiation component during warm months
   - Optimize glass thermal quality and solar transmittance capacity per orientation
   - Optimize roof thermal and solar reflectance performance
   - Optimize wall and floor thermal performance
2. Minimize building performance load effects
   - Incorporate daylighting to improve visual comfort and to reduce connected ambient light load
     - Modify glass to control solar radiation, but allow visible light transmittance
     - Adjust initial space layout to provide open areas on building perimeter
   - Incorporate passive solar reclaim on south exposure to offset winter heating load
   - Incorporate green roof systems to stabilize year-round plenum temperature
3. Minimize connected internal load
   - Identify a realistic occupant use schedule and integrate with internal load components
   - Optimize applied lighting efficiency and staging controls
   - Maximize efficiency of office equipment
4. Develop HVAC infrastructure based on optimized load profile (for simplicity, other MEP infrastructure system dependencies are excluded from the primary demonstration)
   - Select best-fit strategy for HVAC systems based on minimized building load, use profile, and ventilation requirements. Note that this exercise requires extensive modeling by the HVAC engineer to find the best-fit solution. (For this example, assume that a water-cooled chilled-water plant, hot-water gas boiler plant, gas-fired desiccant dedicated outside air unit, and four-pipe fan-coil terminal units have been shown to provide the best-fit energy performance solution that maintains budget

control. There is no basis to this selection other than to demonstrate subsequent evaluation strategies.)
5. Optimize HVAC systems
   - *Chiller plant*
     - Analyze terminal unit cooling coil selections to determine water temperature differential needed to provide cooling performance, minimize distribution pipe size, and minimize pumping capacity
       - Optimize condenser water temperature differential to find best fit for chiller, cooling tower, and condenser water pumps
       - Evaluate effect of water-side economizers
       - Evaluate application of condenser water heat recovery as a waste heat source
   - *Boiler plant*
     - Analyze terminal unit heating coil selections to determine water temperature differential needed to provide heating performance, minimize distribution pipe size, and minimize pumping capacity
   - *Ventilation system*
     - Analyze effect of energy recovery on dedicated outside air unit and central plant capacities
     - Evaluate distribution options and effect on air horsepower for delivery of ventilation air to the occupied space
6. Optimize HVAC components
   - *Chiller plant*
     - Optimize chiller for best-fit performance compared to projected load profile and condenser water relief opportunities
     - Optimize cooling-tower performance using air or water modulation compared to projected load profile
     - Examine effect of motor efficiency improvements on pumping systems
     - Optimize sizing of noncritical path piping mains and branches
   - *Boiler plant*
     - Optimize boiler performance compared to projected load profile
     - Examine effect of motor efficiency improvements on pumping systems
     - Optimize sizing of noncritical path piping mains and branches
   - *Ventilation system*
     - Examine effect of motor efficiency improvements on fan systems
     - Optimize sizing of noncritical path duct mains and branches

This simple example demonstrates that there are many possible strategies for a project. The magnitude is greatly expanded when multiple objectives are pursued. In the example, note that HVAC system design is not even a factor until development of the least-load-impact building is assembled. Only then do applied MEP system solutions come into focus. The example strategy development supports the object: reduce energy use by minimizing load, right-sizing systems to meet the load, and then maximizing component efficiency to match the use profile.

Iterative Evaluation and Analysis

As the example strategy for minimizing energy use demonstrates, there are multiple development steps that must be followed in pursuit of IBD objectives. Design of the final product depends on looking at each system-level component contribution and determining whether incorporation of the proposed strategy improves the project whole within the guidelines of the decision criteria.

As each strategy is explored, numerous *what-if* questions must be evaluated and accepted or discarded. Acceptance allows the team to move forward, but does not preclude returning for reevaluation later. Nonacceptance may progress into alternative solutions for the

target strategy, or it may lead to totally discarding the strategy and moving forward. Discarding a strategy does not preclude returning to it later.

Obviously, IDP requires significant effort and creativity to (1) develop applicable strategies to meet project objectives, (2) refine strategy flow as the building evolves, (3) define component variables as each strategy is evaluated, (4) analyze the financial effects of each strategy, and (5) repeat the process over many iterations.

DESIGN ACTIVITIES AND DELIVERABLES

Some of the more common design activities and deliverables are affected by IDP. Some schools of thought suggest that these items be decoupled from integrated practice, but this perspective unfortunately misses the underlying premise that all activities in the project delivery process have a certain level of interdependency. When collaborative design strategies are used, these interdependencies require increased stewardship.

Drawings

The drawings are graphic representations of the work on a project, and include plans, elevations, sections, details, legends, notes, abbreviations, and schedules. They are often diagrammatic, and rarely show every detail required to construct a facility. Drawings show quantities, extents, and spatial relationships of the elements of construction to each other and existing conditions and surroundings. They may identify a particular product, material, finish, or process many times. However, the particular product, material, or process should be specified only one time in the specifications. Descriptions and identifiers on the drawings should be simple, concise, and generic. IBD does not change this basic definition.

IBD does have an effect when it comes time to communicate the system solutions onto drawings that will be used for construction. Coordination now becomes an appropriate and critical IDP tool. The project team must take time to ensure that the integrated work results are correctly identified throughout the drawing set.

The project team should avoid issuing drawings in decoupled groups or individual sheets during the procurement phase. Bidding in isolation is just as detrimental as design in isolation when it comes to achieving integrated solutions.

Specifications

The project manual is the textual description of the work and other requirements for a project; it includes procurement and contracting requirements, general requirements, and technical specifications for the work of the project.

Specifications describe the administration, quality, products, materials, workmanship, warranty, testing, and start-up requirements of the work of a project (CSI 2005). For uniformity in structure, location of information, consistency, and quality control, it is best if the specifications are organized into divisions and subdivisions (sections) that correspond to the major divisions of work required to complete the project as defined in *MasterFormat* (CSI 2004).

The 2004 edition of *MasterFormat* includes some very powerful new sections to assist in IBD delivery, including the following level 2 and 3 additions to division 01, General Requirements:

- 01 33 00, Submittal Procedures
  - 01 33 29, Sustainable Design Reporting
- 01 78 00, Closeout Submittals
  - 01 78 53, Sustainable Design Closeout Documentation
- 01 81 00, Facility Performance Requirements
  - 01 81 13, Sustainable Design Requirements
  - 01 81 16, Facility Environmental Requirements
  - 01 81 19, Indoor Air Quality Requirements
- 01 86 00, Facility Services Performance Requirements
  - 01 86 19, HVAC Performance Requirements
  - 01 81 23, Integrated Automation Requirements
- 01 91 00, Commissioning
  - 01 91 13, General Commissioning Requirements
- 01 92 00, Facility Operation
  - 01 92 13, Facility Operation Procedures
- 01 93 00, Facility Maintenance
  - 01 91 13, Facility Maintenance Procedures

Tools are in place in the industry to support communication of integrated system design into work results that can be consistently located. Further study of the *MasterFormat* structure will demonstrate that individual facility services, such as HVAC, have defined specification structures to support effective communication of system solutions.

Value Engineering

Value engineering (VE) is similar to life-cycle cost analysis, and may be performed at any phase of design. It is most often performed when potential construction cost overruns have been identified, or alternative systems or substitute equipment is being considered. Applying the same methods described for life-cycle cost analysis, the alternative system or component being value engineered should be analyzed for its total ownership cost effect. The results should then be compared to the project objectives to see if incorporation has merit.

When VE is complete, recommendations should be made to the owner describing the process and methods used to determine the total cost of the system(s) analyzed. The system that best suits the owner's needs and expectations should be indicated. Recommendation of proposed VE alternatives should indicate how the defined project objectives are affected.

Risk Management

Risk management includes the following:

- Systematic, consistent application of written standard office procedures
- Judicious implementation of QA/QC procedures
- Comprehensive record keeping
- Timely and accurate communications
- Written contracts that include certain basic terms and conditions for all services rendered

Because IDP involves significant collaboration, team members need to practice a policy of keeping good, complete, contemporaneous records of the facts discussed and decisions made (and by whom) in meetings, during site visits, in e-mails, and during telephone conversations. Most errors and omissions (E&O) and liability insurance carriers and their legal counsels offer guidance, and customarily provide publications on risk management as part of their service to their insured. Team members should be well versed in how to practice proactive risk management so that liability paralysis does not reduce collaborative participation.

Budget Control

Traditionally, there are two types of budgets the design team must manage during the design phase: design cost and construction cost. Note that this is not an absolute, because there could be a deviation if progressive-thinking owners incorporate all or portions of operating-related budgets into the equation.

Design cost control begins with design team resource allocation, budgeting, and scheduling while preparing the fee proposal. Once a complete scope of work has been defined, a project budget analysis should be prepared and submitted with the fee proposal to the client. In the SDP model, regular monitoring of actual design cost as compared to the original project budget analysis and scope of work should help avoid scope creep and ensure that projects are delivered

within the design fee budget. The IDP model requires that design fee budget control include an additional oversight element. Although infinite evaluations may lead to the absolute best built solution, design fee structures have a practical limit on how many evaluations are affordable. It is therefore financially critical for the design professional to develop a clear strategy at the time of fee negotiation so that all parties agree on the extent and quantity of strategy evaluations, how the fee is structured to reflect the applied effort at the time of service, and how additional services are accommodated if additional evaluations are required.

Responsible control of construction cost budgets can vary depending on the project delivery model. Design-bid-build models place the design team in an oversight role. Design-build allows the contracting entity to control cost of the delivered solution. Design-CM brings in a third-party construction manager, who is responsible for delivery of the project within the defined construction budget. IBD is achievable under any of these delivery models. Each requires, however, accurate cost projections to support realistic system evaluation. Likewise, the construction budget needs to represent a level of funding that supports construction of the final system solutions. Cost projection and cost control play hand-in-hand throughout the iterative evaluation process.

Constructability Review

Constructability is a measure of how well construction documents provide the construction team with the information necessary to complete and deliver a project that meets the owner's expectations and documented project requirements. A constructability review is an organized process of reviewing construction documents during the design phases to make recommendations to the owner and design team about how the design may better define expected construction work results. The IDP is well served when knowledgeable construction representatives provide objective feedback on the constructability of developing system solutions.

Operational Review

Operational reviews should be conducted during the design development and construction document phases of design. Depending on the owner, this type of review may be increased to correspond with evaluation scenarios. Operational review can also be one of the decision-making criteria used on a project.

Reviewers should be knowledgeable about systems, equipment, controls, operation, and maintenance. Ideally, the review should include representation from the group that will be ultimately responsible for operating the facility. During the review, sequences of operation should be thoroughly reviewed to ensure that integrated solutions are truly integrated. Equipment location should be reviewed to verify that required maintenance clearance and accessibility are provided. Drawings and specifications should be checked to ensure that (1) the appropriate level of system and component commissioning has been prescribed, (2) adequate and usable close-out documentation has been itemized, and (3) sufficient training has been scheduled for operational staff.

Operational constraints must be considered when system solutions are developed. Nonconventional systems and equipment can be somewhat intimidating for building operators. The issues of perceived complexity and risk must be mitigated. Solutions must be kept in perspective with the client's ability to operate and maintain the facility. Operational review is an excellent process to address these concerns.

Commissioning

Commissioning is a systematic process of applying QA/QC procedures to the design and construction of a building, to verify that key elements of the design are, in fact, constructed as designed, and started, tested, operated, and maintained so that the building meets the designer's intent and owner's expectations.

ASHRAE defines commissioning of HVAC systems as "the process of ensuring that systems are designed, installed, functionally tested, and capable of being operated and maintained to perform in conformity with the design intent. Commissioning begins with planning and includes design, construction, start-up, acceptance and training, and can be applied throughout the life of the building" (ASHRAE *Guideline* 1).

Commissioning is a rigorous and intense process that should be used when integrated-system-based design solutions are provided. See Chapter 42 for more information.

PROJECT DELIVERY SEQUENCE FOCUS

IDP applies to all phases of project delivery, not just the standard design phases. Successful delivery requires that the entire project team contribute to their role at the appropriate time. The project team should be cognizant of the unique effort focus required within each phase. The following outline identifies key focus elements that IDP should consider:

- Owner planning
  - Determine best-fit construction need
  - Identify least-impact, best-fit siting option
  - Define project objectives
  - Structure project delivery budget to support IDP delivery
  - Select team to support project objectives
- Predesign
  - Refine project objectives
  - Define decision-making criteria
  - Develop strategies to support project objectives
  - Develop initial program solution
- Schematic design
  - Develop facility solution assembly
  - Optimize facility systems
  - Apply facility services solutions to support optimized facility
- Design development
  - Optimize all facility and services systems
- Construction documents
  - Optimize all facility and services components
  - Communicate system solution accomplishments into constructable work results
- Procurement
  - Provide oversight to ensure that procurement document revisions do not negatively affect developed system solutions
  - Adjust project objectives and conduct new strategy evaluations as required to respond to dynamic scope modifications
- Construction
  - Adjust project objectives and conduct new strategy evaluations as required to respond to dynamic scope modifications
  - Provide oversight to ensure that product substitutions and contract document revisions do not negatively affect developed system solutions
  - Provide oversight of facility and services construction to ensure that work results comply with design intent
- Operation
  - Verify that systems and components operate as intended across all seasonal and usage conditions
  - Verify that operational staff fully understand how systems work holistically
  - Verify that applicable maintenance procedures and plans are understood to support systems and components for the facility life cycle.

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RESOURCES

BLLC	www1.eere.energy.gov/femp/information/download_bllc.html
DOE2 and Energy10	www.eere.energy.gov/buildings/highperformance/simulation_software.html
EnergyPlus	www.eere.energy.gov/buildings/energyplus/
eQuest	www.doe2.com/equest

CHAPTER 58

CHEMICAL, BIOLOGICAL, RADIOLOGICAL, AND EXPLOSIVE INCIDENTS

THIS chapter considers chemical, biological, radiological, and explosive (CBRE) incidents that do not cause major structural damage to a building or its infrastructure. It is not intended to be used for design or development of life safety systems or procedures, or for protection of personnel during an incident; rather, it offers descriptions of some CBRE incidents and their associated effects on buildings, building equipment, and occupants, and offers general guidelines for how to deal with their effects on building infrastructure. Since September 11, 2001, more published information has been available about procedures for preventing, mitigating, and remediating terrorist or other CBRE incidents. ASHRAE's (2003a) *Report of Presidential Ad Hoc Committee for Building Health and Safety under Extraordinary Incidents* discusses many aspects of buildings, building infrastructure, and measures that can both reduce the threat and/or damage from such incidents. Several departments of the U.S. federal government, including the Federal Emergency Management Agency (FEMA), Department of Homeland Security (DHS), National Institute for Occupational Safety and Health (NIOSH), Centers for Disease Control (CDC), and Department of Defense (DOD), have produced reports and guidelines for dealing with terrorist threats to buildings (see the Bibliography). Emphasis is generally on actions to reduce the potential harm to building occupants, both by reducing the threat and by instituting procedures that reduce the hazard during an incident.

In almost any case of a terrorist event affecting a building, its infrastructure, or its occupants, the affected building and its immediate surroundings are likely to be in police or military control for several days (or longer) after the event. During this period, the role of the building(s) owner or physical plant staff is to assist in controlling or remediating the affected areas through their knowledge of the building and its infrastructure systems. Assessment of damage or remaining danger to the building or personnel is difficult, particularly with chemical, biological, and radiological events, in which the contaminating agent often is invisible and is only revealed through adverse health effects. As such, there are no specific guidelines for how or when a building can be brought back online and readied for occupancy; each event is unique. Any preparation or response protocol for CBRE incidents internal or external to the facility should be designed to consider the specifics of the building and its occupants. It is impossible to provide general guidelines for incidents that are so unpredictable and potentially so devastating. This chapter attempts to shed light on some of the possible effects to buildings, their systems, and their occupants, which may aid in the development of a more specific protocol in line with a particular facility's needs.

CHEMICAL INCIDENTS

A chemical incident is defined as the accidental or intentional release of a gaseous or vaporous compound into breathable air. Releases of toxic liquids, solids, or powders are not addressed in this chapter. A release may occur inside or outside a building, and may be of short duration (e.g., from a broken container, an accidental valve opening, or a terrorist incident) or sustained (e.g., from a leaking storage tank or broken supply line). Descriptions of classes of and individual air contaminants, including chemicals, are found in Chapter 12 of the 2005 *ASHRAE Handbook—Fundamentals*, and removal techniques are covered in Chapter 25 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment* and Chapter 45 of this volume. Discussions in this chapter are limited to chemicals that are considered acutely toxic or corrosive, and present immediate danger to building occupants or systems.

Industrial buildings, where harmful chemicals may be used routinely, are likely at higher risk for internal chemical incidents than a typical commercial building, but, because of training, established procedures, and experienced personnel, they are also likely to be more prepared to handle an incident. Most commercial buildings, except for some government and high-profile buildings, do not have procedures in place for handling a chemical incident. A terrorist chemical event on a typical commercial building adds new difficulties, because details of the release are not known until long after the incident, and affected buildings and occupants are generally caught off guard, with little or no procedure in place for handling the event.

Chemical substances that can cause physical distress when introduced into breathable air are numerous; this chapter addresses only gaseous or vaporous compounds, and of those, addresses only two groups (1) those specifically known as chemical agents (in terms of warfare/terrorist activities) that might be intentionally introduced into a building's environment, and (2) a few common industrial gaseous substances that might accidentally be introduced into a building HVAC system through external or internal release, thus requiring HVAC or facility remediation of some kind. The purpose of this section is to address buildings that have no expectation of an accidental chemical release, based on the activities performed within the facility, as opposed to those of surrounding, related facilities (e.g., industrial facilities that have their own response plans). For control of airborne gases and vapors that are used as part of the building's normal operation, such as in laboratories or industrial processes, see Chapter 25 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment* and any of the application-specific chapters in this volume.

TYPES OF CHEMICAL AGENTS

Intentional contamination of facilities and their HVAC systems (and thus very ready dispersion to occupants) with gaseous or

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The preparation of this chapter is assigned to TRG2.BCBR, Blast, Chemical, and Biological Remediation.

vaporous chemical substances has become a real concern. Chemical agents are classified by the U.S. Army *Fact Sheets* either as toxic or incapacitating. Toxic chemical agents include nerve, blister, lung-damaging, and blood agents. Any of these agents may be introduced in sufficient quantity so as to injure building occupants and, in the process, compromise the building's HVAC system. Irritating agents (e.g., tear gas), which cause temporary trauma through reflexive action but are not generally lethal, are not considered by the U.S. military to be chemical agents.

Incapacitating Agents

Incapacitating agents are defined by the U.S. DOD as chemical agents that produce temporary physiological or mental effects, or both, that make individuals unable to make a concerted effort to perform their assigned duties. In occupational medicine, *incapacitation* generally means *disability*, and denotes the inability to perform a task because of a quantifiable physical or mental impairment. Thus, by definition, any of the chemical warfare agents may incapacitate a victim; however, by the military definition, incapacitation refers to impairments that are temporary and nonlethal, and does not include low-dose "lethal" agents. Incapacitating agents may cause symptoms that persist for hours to days, but are temporary and recoverable even without treatment. Common incapacitating agents include

- 3-quinuclidinyl benzilate (BZ)
- Cannabinols
- Phenothiazines
- Fentanyls
- Central nervous system stimulants [e.g., d-lysergic acid diethyl amide (LSD)]

These agents act by either depressing or stimulating the central nervous system (CNS). Symptoms of poisoning by these agents include confusion, disorientation, restlessness, dizziness, staggering, or vomiting. Some may cause dryness of mouth, elevated temperature, pupil dilation, slurred/nonsensical speech, inappropriate behavior, and hallucinations. If several personnel exhibit any such behavior, it is prudent to move outside the building, because these agents are usually delivered by smoke-producing munitions or aerosols and are introduced through the respiratory system.

Irritants

The sole purpose of irritants, which include tear gas, riot control agents, and lachrimators, is to produce immediate discomfort and eye closure, thus rendering the victim incapable of fighting or resisting. Irritants cause eye discomfort, and some may cause vomiting; all are usually introduced to an environment as a gas. Police forces use them for crowd control. They were used before World War I, and, during the war, they were the first chemical agents used, well before better-known agents such as chlorine, phosgene, and mustard gas.

Tear gas (CS) and chloroacetophenone (CN; sold in diluted form as a protective spray) are by far the most important pulmonary irritants. Capsaicin (methyl vanillyl nonenamide) is the active ingredient in pepper spray, also called OC (oleoresin capsicum). Pepper spray has, to some extent, replaced CN as a personal protective agent, with less dangerous effects. As its common name implies, the active ingredient is the burning agent in pepper plant fruits.

Although CS and CN are the most important agents in this class, several others require mention. Chloropicrin (PS) and bromobenzenecyanide (CA) were developed before World War I. Both largely have been replaced, because they were too lethal for their intended effects but not lethal enough to compete with the more effective blistering and nerve agents. PS still is used occasionally as a soil sterilant or grain disinfectant.

Toxic Chemical Agents

Nerve Agents. Nerve agents are among the deadliest of chemical agents and may produce symptoms rapidly. Some nerve agents include

- VX
- Tabun (GA)
- Sarin (GB)
- Soman (GD)
- Cyclosarin (GF)

Nerve agents may be absorbed through any body surface (skin, eyes, respiratory) or ingested. Symptoms of nerve agent poisoning include

- Sweating and/or muscular twitching
- Pupil contraction, eye pain, or blurred vision
- Headache, pain
- Weakness
- Nausea, vomiting (particularly in ingestion)
- Mucous secretions in respiratory pathways, nose, or throat
- Wheezing, coughing
- Severe exposure: convulsions, vomiting, red pinpoint eyes, unconsciousness, or respiratory failure

Mild exposure to nerve agents may cause anxiety, restlessness, and giddiness. Further exposure results in the listed symptoms and/or memory impairment, slowed reactions, or difficulty in concentration. Moderate exposure, if diagnosed and monitored, shows abnormalities in electroencephalograms (EEGs) as well as the symptoms listed. Reactions to nerve agents are immediate (i.e., within minutes of exposure). Recovery from nerve agent exposure is slow, usually days, and susceptibility to the agent is increased for months afterward.

Nerve agents are liquids at room temperature. However, some are highly volatile and therefore would be easy to introduce as vapors through an HVAC system. Others have a relatively low volatility but can be introduced as droplets or vapor by mechanical means. Those that are highly volatile are generally not persistent (i.e., disperse quickly) unless thickened with various chemicals to make them persistent. VX, for example, is naturally persistent (with a relatively low volatility) and would require intense cleanup were it to be introduced to a building. For the most part, these agents are moderately soluble in water and highly soluble in lipids. They are rapidly inactivated by strong alkalis and chlorinating compounds, which are used in the decontamination/neutralization of these agents.

If nerve agents are suspected, evacuate the facility immediately. Because many nerve agents are (or can be made) persistent and dose is accumulative, evacuation is necessary. A facility must be decontaminated if exposed to nerve agents.

Blister Agents. Blister agents (vesicants) include the well-known mustard gas. These agents are generally used as warfare agents meant to degrade fighting efficiency rather than to kill. They are usually thickened to make them persistent and contaminate surfaces, but may be introduced as a gas or vapor. Vesicants result in burns and blisters to the skin, eyes, and/or respiratory tract. Types include

- Sulfur mustard (H and HD)
- Nitrogen mustards (HN)
- Lewisite (L)
- Halogenated oximes [e.g., phosgene oxime (CX)]

The most likely routes of exposure are inhalation, dermal contact, and ocular contact. Depending on the particular vesicant, clinical effects may occur immediately (as with phosgene oxime or lewisite) or may be delayed for 2 to 24 h (as with mustards). Blister agents must be cleaned from the skin and membranes immediately to lessen their effects. Persons exposed to blister agents must be handled so as not contaminate those helping them. Evacuation is

necessary, and contaminated people should be kept outdoors to prevent accumulation of the vesicant in a confined space. Effects of exposure include

- Mild to severe conjunctivitis, possibly progressing to ulceration
- Lesions on skin; burns
- Itching
- Pain (immediate with exposure to lewisite)
- Respiratory damage (in small doses may take time to appear as bronchitis, etc.)

Vesicants are, for the most part, soluble in nonaqueous solvents, not in water. They are more dangerous as liquids, because the degree to which they cause health problems is related to their concentration on body surfaces. In general, they have high vapor pressures and thus are easily vaporized in a confined space. Decontamination of exposed surfaces is needed.

Lung-Damaging Agents. Lung-damaging (choking) agents are those that primarily attack lung tissue, causing pulmonary edema. Examples include

- Phosgene (CG)
- Diphosgene (DP)
- Chlorine
- Chloropicrin (PS)

As choking agents, most of these agents (except for diphosgene) exist as gases at room temperature and pressure, and are thus easily spread through ventilation systems. Exposure symptoms include

- Choking sensations, coughing
- Tightness in chest
- Nausea, vomiting
- Headache

Because these agents are gaseous, they will disperse. They all have specific odors; for example, CG smells like fresh mown hay. Thorough ventilation of contaminated areas is necessary. Choking agent gases typically are heavier than air, and thus tend to accumulate in low-lying areas.

Blood Agents. Blood agents, also known as cyanogens, interfere with the absorption and use of oxygen at the cellular level, and thus are usually introduced through the respiratory system. Examples include hydrogen cyanide (AC) and cyanogen chloride (CK). These agents are highly volatile and gaseous at temperatures over 70°F. They therefore dissipate quickly in air, especially hydrogen cyanide, which is light; cyanogen chloride is heavier than air and tends to collect in low places. These two blood agents have different symptoms. Symptoms of exposure to AC include

- Faint odor of almonds
- Internal hemorrhaging
- Pink skin color
- Highly toxic, high concentrations can cause immediate death

CK symptoms include

- Intense irritation to the lungs and eyes
- Coughing
- Tightness in chest
- Dizziness
- Unconsciousness
- Respiratory failure

Because these agents are not persistent, thorough ventilation should dissipate the gases.

Other HVAC-Compromising Gases and Vapors

Accidental contamination of facility HVAC systems by gaseous or vaporous chemical substances has been a real concern for years, mainly because of the extensive production, use, and transport of large quantities of hazardous materials for manufacturing purposes.

Intentional contamination of a facility could be accomplished with chemicals other than the specific chemical agents discussed previously. Contamination internal to a building should result in immediate evacuation. However, external contamination might entail evacuation to a more distant location or shelter in place (i.e., do not evacuate). Contamination from an incident in the immediate vicinity of (but external to) a facility might require shutdown of the facility's HVAC system for a short period of time. For instance, a large corrosive spill nearby might necessitate staying in a building for protection while transportation is arranged (if not available immediately). This might occur at a school where children would be more susceptible to injury upon exiting the building, having no way to evacuate a safe distance. Because the situations and possibilities are so varied, this discussion is limited to some more typical scenarios.

Toxic Gases. The most common toxic gas that might threaten a facility and its personnel is carbon monoxide (CO), which is colorless, odorless, and tasteless. Carbon monoxide is produced by incomplete combustion of fossil fuels (gas, oil, coal, wood) used in boilers, engines, oil burners, gas fires, water heaters, solid-fuel appliances, and open fires. Dangerous amounts of CO can accumulate when, as a result of poor installation, poor maintenance, or failure, an appliance's fuel is not burned properly, or when rooms are poorly ventilated and the carbon monoxide is unable to escape. Because CO has no smell, taste, or color, it is important to have good ventilation, maintain all appliances regularly, and have reliable detector alarms installed to give both a visual and audible warning in case of a dangerous build-up of CO. Scenarios involving toxic gases usually entail evacuation to a safe distance. HVAC systems normally require cleaning using clean purge air the through the ventilation distribution system.

Corrosive Substances. Corrosive gases and vapors encompass a large class of materials. A few are purely gaseous in nature at room conditions, but some vapors result from the vapor pressure created by a liquid (or solid) presence. Some examples of corrosive gases and vapors are given in Table 1.

Corrosive gases and vapors are hazardous to all parts of the body, although some organs (e.g., eyes, respiratory tract) are particularly sensitive. The magnitude of the effect is related to the solubility of the material in body fluids. Highly soluble gases (e.g., ammonia, hydrogen chloride) cause severe nose and throat irritation, whereas lower-solubility substances (e.g., nitrogen dioxide, phosgene, sulfur dioxide) can penetrate deep into the lungs. Exposed skin may also be at risk for irritation or burns at higher concentrations or longer-term exposures. For some substances, warnings such as odor or eye, nose, or respiratory tract irritation may be inadequate. Accidents involving corrosive substances inside or outside a building require cleanup and decontamination of the facility's HVAC system and other equipment, because of the substances' persistence. In some cases, physical damage to a building's infrastructure may result from exposure to corrosives (e.g., etching of metal surfaces, which can lead to holes in ducting, and compromised wiring). Building codes outline methods of design and installation for mechanical and electrical systems in corrosive environments (NFPA 2005), but in buildings that are not classified as such, and thus are not constructed

Table 1 Corrosive Gases and Vapors

Corrosive Gases	Corrosive Acidic Vapors	Corrosive Basic Vapors
Hydrogen cyanide	Hydrochloric acid	Sodium hydroxide
Ammonia	Sulfuric acid	Ammonium hydroxide
Sulfur dioxide	Nitric acid	Caustic soda
Chlorine	Hydrofluoric acid	Potassium hydroxide
Hydrogen bromide	Acetic acid	Other hydroxides
Boron trichloride	Other acids	
Monomethylamine		
Phosphorus pentafluoride		

accordingly, systems may be damaged when exposed to corrosive chemicals. In such a case, the building and its systems should be thoroughly inspected and tested before reoccupation.

BIOLOGICAL INCIDENTS

Biological incidents involve the intentional or accidental release of unwanted bioaerosols and/or biocontaminants in or around a building, such that the building's integrity or usefulness is compromised. Bioaerosols are airborne particulates derived from living organisms and include living microorganisms, viruses, spores, and toxins derived from remnants or fragments of living tissue. Bioaerosols are in the air, both indoors and outdoors, and their presence mostly goes unnoticed except for seasonal allergies or an occasional cold. There is an evolved balance between the types and levels of bioaerosols in the ambient air and the animals who breathe that air. That balance can be disturbed locally by the purposeful or accidental release of a bioaerosol in or around a building. Unfortunately, bioaerosols are difficult to detect and identify in real time, because identification generally involves DNA analysis or other skilled analytical techniques. As a consequence, bioaerosols may be fully distributed in a building hours or days before anything is detected, much less identified, and the first sign of an incident may be symptoms of personnel.

There are hundreds of known bioaerosols that are pathogenic to humans to varying degrees. These include the spore-forming bacteria *Bacillus anthracis* (commonly known as anthrax), *Variola spp.* (the virus that causes smallpox), the bacteria *Yersinia pestis* (cause of bubonic plague), and many others. Human susceptibility varies by microorganism, and is gaged by several dose measures:

- **ID_{50}, mean infectious dose**, is the number of microorganisms or bioaerosol particles that causes 50% of an exposed population to be infected.
- **LD_{50}, mean lethal dose**, is the number of microorganisms or bioaerosol particles that causes death in 50% of an exposed population.

A summary of potential bioaerosol weapon agents is given in Table 2 along with ID_{50} and LD_{50} values. A more comprehensive list can be found in Kowalski (2003). More detailed descriptions of bioaerosols, their health effects, and methods of measurement can be found in most epidemiology texts. *Bioaerosols: Assessment and Control*, from the American Conference of Governmental Industrial Hygienists (ACGIH 1999), is a recommended starting point for quantitative determination of bioaerosol levels. General information on bioaerosols, their health effects, and their removal from building airstreams is found in Chapters 9 and 12 of the 2005 *ASHRAE Handbook—Fundamentals*, as well as Chapter 24 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*.

The primary threat to buildings from airborne biological incidents is adverse health effects to building occupants. Once an event happens, there is an immediate danger to building occupants from the initial dose, but there is also the risk of prolonged exposure from contaminated surfaces and reaerosolization of the agent. Depending on the agent, the prolonged exposure risk may dissipate quickly if the

Table 2   Limited List of Human Pathogenic Microorganisms

Bioaerosol	Incubation Period, Days	ID_{50}, Organisms	LD_{50}, Organisms
Bacillus anthracis (anthrax)	2 to 3	10,000	28,000
Ebolavirus spp. (Ebola)	14 to 21	10	Low
Francisella tularensis (tularemia)	1 to 14	10	Low
Hantavirus (Hanta)	14 to 30	N/A	N/A
Variola spp. (smallpox)	12	N/A	N/A
Yersinia pestis (bubonic plague)	2 to 6	N/A	N/A

pathogenic organism has a short life outside of a host, or it may remain indefinitely until the contaminating agent is fully removed. Anthrax, which is a spore-forming bacterium, falls into this later category because it can lie dormant in many environments for long periods of time, only to come out of dormancy when exposed to a proper host. Excluding incidents of extreme mold growth [which is not covered in this chapter; see, e.g., ASHRAE (2003b) for information], biological incidents present no real threat to the integrity of building equipment; however, building equipment may play an important role in both distribution and possible removal of air contaminants. Remediation after an incident is likely to involve comprehensive cleaning of building equipment (particularly air-handling equipment), and may require removal and replacement of contaminated systems. Techniques for remediating contaminated equipment include surface cleaning with bleach or alcohol solutions, treatment with ultraviolet (UV) light, and volume gaseous treatments with ozone, hydrogen peroxide, or gas plasma. New technologies and procedures are under development, particularly since the anthrax events of 2001 in the United States. See the Bibliography and Online Resources for sources of information on the latest developments in remediation technology.

It is important to determine as much as possible about a release, whether purposeful or accidental, as rapidly as possible. It may be more difficult to completely assess the nature of a purposeful release, because it may contain more than one pathogenic agent, with different incubation periods, and the release may have taken place in several locations. Accidental releases are more likely to be a single pathogen at a single location, and the release is more likely to have been known to occur.

Biological pathogens have been weaponized to enable delivery in a variety of forms. Effective delivery of bioagents to a large population is difficult because of the need to get relatively large doses to large numbers of people. Dilution of contaminants in ambient air is rapid, and very large numbers of organisms are required to produce lethal concentrations. The confines of a building and controlled air exchanges rates can help maintain concentrations of agents for longer periods of time than would occur in outdoor air. However, filtration and real-time killing mechanisms in building air-handling systems can remove or render ineffective airborne bioaerosols. Engineering requirements for design of filtration or other techniques for treating indoor air are addressed more fully in other publications [e.g., NIOSH (2003)]. Information is rapidly evolving; for the latest, consult the most recent versions of publications on building protection.

RADIOLOGICAL INCIDENTS

The occurrence of a significant accidental or intentional radiological release to the environment is of low probability because there are limited locations where considerable amounts of radiological material reside. These sources include spent fuel or low-level radioactive waste (radwaste) storage facilities, nuclear generating stations, and weapons fabrication and storage facilities. These facilities are usually analyzed beforehand, as part of the construction licensing process, for postulated accidental releases of radiological material and the consequences to both on- and off-site personnel.

An intentional release of radiological material is most likely to be in the form of the deployment of a nuclear weapon or a radiological dispersal device (RDD), sometimes called a dirty bomb. It is normally assumed that a terrorist group is highly unlikely to possess and use conventional, sophisticated nuclear weapons because of the difficulties of obtaining or independently developing the necessary materials and technology. Development and deployment of an RDD, however, is considered viable because of its simplicity of design. RDDs combine conventional explosives and radioactive material, and are designed to scatter dangerous amounts of radioactive material over a general area. Terrorist use of RDDs also seems more likely because radiological materials used in medicine, agriculture,

industry, and research are comparatively more obtainable than weapons-grade uranium or plutonium. A significant amount of the damage from an RDD would be from the initial blast. See the section on Explosive Incidents for design of HVAC system protection against blast effects.

RADIOACTIVE MATERIALS' EFFECTS AND SOURCES

Decay of radioactive materials produces energetic emissions (ionizing radiation) that can effect changes in human tissue cells. These energetic emissions are divided into **alpha** particles, **beta** particles, and **gamma/x-rays**. Alpha and beta radiation can only travel very short distances (several feet, maximum) and do not have enough energy to penetrate the outer layers of human skin; they are, however, a hazard if directly inhaled or ingested. Gamma and x-rays can travel long distances in air and can pass through the body, potentially exposing internal organs to significant damage, depending on the amount absorbed. The radiation effect on humans is usually measured in röntgen equivalent man (rem), the product of the absorbed dose and the biological efficiency of the radiation.

In developing an RDD, a significant quantity of radioactive material must first be collected. Some common radioactive materials currently used in industry include

- Colbalt-60 (Co-60), cesium-137 (Cs-137) and iridium-192 (Ir-192) are used in cancer therapy, industrial radiography and gages, food irradiation, oil well production, and medical implants. These are all considered gamma emitters.
- Strontium-90 (Sr-90) is used in the production of radioisotope thermoelectric generators (RTGs), which produce electricity for remote devices such as spacecraft. This is considered a beta emitter.
- Plutonium-238 (Pu-238) and americium-241 (Am-241) are used in oil well production, RTGs, and industrial gauges. These are considered alpha emitters.

RADIOLOGICAL DISPERSION

Dispersion may be by conventional explosives, using aircraft to disperse the material in the form of an aerosol or particulate, or simply placing a container of radioactive material within a confined area or facility. In most cases, a dirty bomb or other RDD would have localized effects (based on the strength of material used) ranging from less than a city block to several square miles. The area affected by the dispersion of the material is a function of various factors, including

- Meteorological conditions, including atmospheric stability and wind speed
- Local topography, location of buildings, and other landscape characteristics
- Amount and type of radioactive material dispersed
- Dispersal mechanism (e.g., particulate, aerosol)
- Physical and chemical form of the radioactive material (e.g., dispersal as fine particles versus heavier droplets or particulate)

Radioactive material released as either an aerosol or fine particulate in a plume spreads roughly at the speed and direction of the prevailing wind velocity. The conditions of atmospheric stability (sometimes referred to in terms of the Pasquill stability classification) also determine the fallout's overall spread and concentration. Atmospheric dispersion computer models are sometimes used to predict the spread, location, and concentration of a postulated radioactive plume. These analytical tools can be useful in providing early warning to residences and facilities projected to be in the affected fallout path.

RADIATION MONITORING

Radioactivity cannot be seen, smelled, or tasted by humans. However, in the United States, there are many radiation-monitoring

programs available at the federal, state, and local level that can measure radiation levels and/or track the released radiation plume. There may be a local facility (e.g., a nuclear power plant) that can track radiological fallout in the affected area. State-level officials have access to various monitoring programs for their areas. These programs use current weather patterns and wind velocities to track radiological plumes and provide public warning. Depending on the severity of the release, the radioactive plume may travel several hundred miles or, more typically, be localized.

FACILITY RESPONSE

Physical safety of personnel should be of primary concern in responding to a radiological event. Time, distance, and shielding are the three most important aspects to minimizing the effects of human exposure to ionizing radiation. Shielding with stone, concrete, or other dense materials is usually not considered in the initial design of most commercial buildings. However, most facilities use these materials for structural strength (foundations and basements) or for fire protection in protective corridors and stairways. Procedures should be considered to instruct building occupants to immediately move to identified safe locations in the facility in the event of a known or suspected release. Limiting the time of exposure to a radiation field also helps reduce the total amount of exposure and subsequent health effects. Distance from the radiation source is the greatest factor in reducing the amount of direct (deep-dose) exposure, especially if the hazard is present for a considerable time period. The distance required to minimize this dose is usually small (several feet).

Perhaps the greatest potential hazard from the release of low-level radiological debris from an RDD is inhalation or ingestion. Health effects from ingested contamination particles that enter the body from breathing, cuts/abrasions, eating, or drinking can be more severe than external exposure, depending on the amount of material consumed. Individuals should be instructed to move to more isolated rooms, or areas within the facility that may be isolated or filtered from significant inleakage of contaminated air. Distribution of personal protection equipment should also be considered by the facility, depending on the risk assessment of a potential threat. If the release is determined to be internal, an organized evacuation should occur (consider developing evacuation procedures). Because evacuees may have become externally contaminated, an egress plan should be considered that includes a radiation detection monitoring procedure implemented either by internal personnel or by local emergency authorities. This procedure may include instruction to dispose of outer clothing and the use of showers to remove radioactive particles from body surfaces.

EXPLOSIVE INCIDENTS

Detonation of high explosives near a building generates pressures that act on all exposed surfaces. The magnitude of pressure depends on the size and shape of the charge, distance from the charge, and any intervening barriers. In addition to increased pressures, blasts may generate projectiles from either loose materials or fragments from damaged components. This section considers only loads that do not generate significant structural damage; it is assumed that, if the structure is severely damaged, continued operation of the HVAC systems is not crucial. Also, it is important to remember that life safety is the primary goal of all protective systems. This section deals strictly with HVAC equipment and systems, but any solutions must not compromise the safety of building occupants.

LOADING DESCRIPTION

Detonation of high explosives generates a pressure wave (blast wave) that propagates out from the explosion with decreasing veloc-
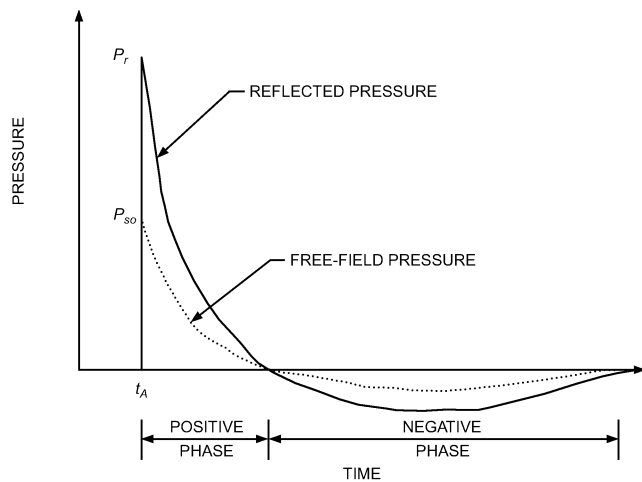
Fig. 1   Free-Field and Reflected Pressure Wave Pulses

ity. The free-field blast wave, far from any surfaces, is characterized by a rapid, almost instantaneous increase in pressure, followed by a gradual decay in pressure and a negative-pressure phase. A typical free-field blast overpressure, reaching the target at time t_A, is shown in Figure 1. When the blast wave impinges on a rigid surface, the pressure is reflected and magnified over the free-field values. Peak pressure varies inversely with the cube of the distance from the explosion. Intervening barriers may reduce the blast load, but quantifying the effect is difficult, and great care must be taken when determining the resulting loads.

Internal explosions can generate extremely large loads on HVAC equipment. In addition to short-duration reflected pressures generated by the explosion, a quasi-static pressure may develop, greatly increasing the impulse to which the equipment is exposed. The magnitude and duration of quasi-static loading is a function of room volume and vented area.

In addition to direct air blast, HVAC equipment in buildings subjected to explosions can experience large accelerations and relative displacements caused by the resulting structure motion. The structure responds to loads imposed both through the foundation (ground shock) and from the air blast (air shock). In general, accurately predicting the time history of motion in the building is extremely difficult. However, because structural design of equipment is based on peak loads, there is usually no need to determine the full time history. Methods are available for predicting the peak motion caused by a given event, including the frequency dependence of the response.

Blast loads can also enter the interior space of buildings through utility openings, even if the building shell is undamaged. The blast can damage the passageway itself, and can also build up pressure within the building and subsequently damage other equipment. Pressure build-up depends upon the opening area and volume of interior space, as well as the pressure differential.

Explosions can produce primary and secondary fragments that may damage equipment and piping. Primary fragments are generated from the explosive casing, whereas secondary fragments result from damage to the structure and nonstructural components (e.g., concrete spalling, glass breakage). Predictions of fragment size and velocity can be used to estimate damage to equipment, ducts, and piping.

DESIGN CONSIDERATIONS

The best protection from any explosive effects is to locate equipment in a nonvulnerable area. Assuming the exterior building shell is adequately designed, any interior room may be considered protected. Barrier walls can protect equipment that must be externally located, or the equipment can be positioned at sufficient distance

from any possible blast location that pressures are reduced below damaging levels. In general, correctly locating equipment is the least expensive option for handling blast loads. Hardening the equipment, anchorage, and connection should be considered only after relocation has been eliminated as a possibility.

In addition to the direct air blast, equipment in a building subject to a blast experiences a support shock loading. Guidelines for the maximum shock that can be withstood by various equipment types are given in the ASHRAE Handbook (e.g., Chapter 54). Although general information can be obtained from these tables, it is important to realize that the data are several decades old and may not apply to modern HVAC equipment. If the shock is greater than the equipment's capacity, it may be possible to provide a shock isolation system to lower the demand. The isolation system works by decoupling horizontal motion of the support structure from that of the equipment. Note that this is different from typical equipment isolation applications, which are generally concerned with vertical vibrations of the equipment itself.

Although it has been stated that proper seismic design will also protect against blast loads, this is not generally true. The effect of blast loading on equipment has some similarities to that of seismic loads, but there are some key differences. Both loads generate horizontal and vertical forces that act on equipment. However, in both magnitude and distribution, seismic forces are proportional to equipment mass, whereas blast loads are proportional to the equipment surface area. The effect is essentially the same for some types of equipment, such as pumps, where the mass and surface area distributions are approximately identical. However, equipment covered by a sheet metal shell is loaded very differently. Seismic loads are applied directly to the heavy components within the shell, whereas blast loads are applied to the shell itself, with little or no load acting directly on the interior components. Thus, even equipment that has been seismically rated or certified needs additional investigation for blast resistance.

In contrast, anchorage design is identical for blast and seismic loads. Properly designed seismic anchorage for most equipment in moderate to high seismic zones is adequate for reasonable levels of blast loading. In either case, loads applied to equipment are used to determine shear and uplift loads on the anchorage that are checked against the allowable load for the specific attachment hardware. Although in reality the dynamic reactions from the resulting equipment motion are the actual anchorage force, for nonisolated equipment it is usually conservative to assume a static distribution of the maximum applied loads. This is not always the case for isolated equipment, because resonance of the load, equipment, and isolation system may produce dynamic forces well above those predicted from a static analysis.

When designing HVAC systems for blast load, it is important to remember that there are two types of failure. The first is a temporary loss of service, such as might be caused by tripping a breaker. The second, more serious case involves actual damage to the equipment or system. It is important to determine which scenario is important for the system, and design accordingly. Preventing temporary outages is, in general, much more expensive than preventing a catastrophic failure.

Exposed piping and ductwork are also subject to both pressure and fragment loading. Pressure loading can be carried through proper selection and spacing of supports. The flexure and shear capacities of the pipe or duct, and the capacity of the support, determine the spacing. Fragment effects are more difficult to analyze, because the exact size and velocity of any fragments is impossible to predict. The only way to fully protect against fragments is to locate the pipe or duct where fragment impact is not possible.

Openings in the building for HVAC or other purposes must also be designed for blast effects. HVAC systems can be damaged by pressure propagated through the opening or blockage of the opening. Grilles or louvers can be analytically designed to resist the blast

load, preventing their blockage and allowing continued operation. Additionally, the pressure increase in ducts, and subsequently in interior rooms, can be calculated. Properly designed silencers may reduce pressure in ducts. The design of openings for blast resistance must also be closely coordinated with protection from chemical and biological agents.

HVAC SYSTEM DESIGN

The function of the facility's HVAC system(s) in response to a CBRE incident can be important in mitigating effects on occupants or, in the case of an internal event, on the surrounding environment. Design of the systems' outside air intake is critical in controlling the amount of dust, particulates, and foreign material entering the building. The following should be considered:

- Location of intakes above grade (out of normal human reach)
- Hiding or camouflaging intakes, securing with limited access from roof or other areas, and use of false intakes at lower building elevations
- Ability to isolate outside air intake or use an emergency standby system using high-efficiency particulate air (HEPA) and chemical filtration

Chapter 26 provides design and operational guidelines for HEPA and emergency filtration units.

HVAC systems with HEPA and chemically filtered protection should be designed with the following considerations:

- Transport of contamination may occur during initial stages of the event, if the HEPA filter protection system is a standby unit. Delay in response, either from manual or automatic actuation, may significantly affect overall filtration efficiency.
- The design should consider all building ventilation system intake and discharge flow paths, and airflow patterns in all operational modes should be thoroughly understood.
- Consider providing a clean safe room or area protected by HEPA/emergency filtration.
- Consider operating the general facility at a positive pressure to outside ambient, to reduce unfiltered inleakage.
- Consider zoning the HVAC distribution system, to minimize cleanup costs and potential overall spread of contamination.
- Develop contingency plans/procedures for loss of ventilation or diminished HVAC system capabilities.

RISK EVALUATION

Probably the first activity a facility should consider in evaluating a CBRE incident is assessing the risk and required response. FEMA and other industry organizations have developed various guidance documents and software to assess the risk and appropriate response from both external and internal events. These evaluations consider the following major parameters:

Risk

- Identify potential high-value targets (e.g., nuclear power plants, museums, government buildings)
- Identify delivery systems
- Calculate risk and vulnerabilities
- Classify occupants
- Identify means to reduce vulnerability
- Consider providing personnel protective equipment (PPE)

Evacuation

- Establish safe egress path
- Categorize first responders
- Identify infrastructural support

Decontamination

- Provide PPE
- Implement recovery of HVAC systems
- Address cleanup, waste handling, and disposal (costs are generally high)

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ONLINE RESOURCES

U.S. Centers for Disease Control and Prevention: www.bt.cdc.gov/

U.S. Department of Homeland Security, Ready Web site: www.ready.gov/

CHAPTER 59

CODES AND STANDARDS

THE Codes and Standards listed here represent practices, methods, or standards published by the organizations indicated. They are useful guides for the practicing engineer in determining test methods, ratings, performance requirements, and limits of HVAC&R equipment. Copies of the standards can be obtained from most of the organizations listed in the Publisher column, from Global Engineering Documents at **global.ihs.com**, or from CSSINFO at **cssinfo.com**. Addresses of the organizations are given at the end of the chapter. A comprehensive database with over 250,000 industry, government, and international standards is at **www.nssn.org**.

Selected Codes and Standards Published by Various Societies and Associations

Subject	Title	Publisher	Reference
Air Conditioners	Commercial Applications, Systems, and Equipment, 1st ed.	ACCA	ACCA Manual CS
	Residential Equipment Selection, 2nd ed.	ACCA	ANSI/ACCA Manual S
	Methods of Testing for Rating Ducted Air Terminal Units	ASHRAE	ANSI/ASHRAE 130-1996 (RA06)
	Non-Ducted Air Conditioners and Heat Pumps—Testing and Rating for Performance	ISO	ISO 5151:1994
	Ducted Air-Conditioners and Air-to-Air Heat Pumps—Testing and Rating for Performance	ISO	ISO 13253:1995
	Guidelines for Roof Mounted Outdoor Air-Conditioner Installations	SMACNA	SMACNA 1998
	Heating and Cooling Equipment (1995)	UL/CSA	ANSI/UL 1995/C22.2 No. 236-95
Central	Performance Standard for Single Package Central Air-Conditioners and Heat Pumps	CSA	CAN/CSA-C656-05
	Performance Standard for Rating Large Air Conditioners and Heat Pumps	CSA	CAN/CSA-C746-98 (R2004)
	Performance Standard for Split-System and Single-Package Central Air Conditioners and Heat Pumps	CSA	CAN/CSA-C2656-05
	Heating and Cooling Equipment (1995)	UL/CSA	ANSI/UL 1995/C22.2 No. 236-95
Gas-Fired	Gas-Fired, Heat Activated Air Conditioning and Heat Pump Appliances	CSA	ANSI Z21.40.1-1996 (R2002)/CGA 2.91-M96
	Gas-Fired Work Activated Air Conditioning and Heat Pump Appliances (Internal Combustion)	CSA	ANSI Z21.40.2-1996 (R2002)/CGA 2.92-M96
	Performance Testing and Rating of Gas-Fired Air Conditioning and Heat Pump Appliances	CSA	ANSI Z21.40.4-1996 (R2002)/CGA 2.94-M96
Packaged Terminal	Packaged Terminal Air-Conditioners and Heat Pumps	ARI/CSA	ARI 310-380-04/CSA C744-04
Room	Room Air Conditioners	AHAM	ANSI/AHAM RAC-1-2003
	Method of Testing for Rating Room Air Conditioners and Packaged Terminal Air Conditioners	ASHRAE	ANSI/ASHRAE 16-1983 (RA99)
	Method of Testing for Rating Room Air Conditioner and Packaged Terminal Air Conditioner Heating Capacity	ASHRAE	ANSI/ASHRAE 58-1986 (RA99)
	Method of Testing for Rating Fan-Coil Conditioners	ASHRAE	ANSI/ASHRAE 79-2002 (RA06)
	Performance Standard for Room Air Conditioners	CSA	CAN/CSA-C368.1-M90 (R2001)
	Room Air Conditioners	CSA	C22.2 No. 117-1970 (R2002)
	Room Air Conditioners (1993)	UL	ANSI/UL 484
Unitary	Unitary Air-Conditioning and Air-Source Heat Pump Equipment	ARI	ANSI/ARI 210/240-2005
	Sound Rating of Outdoor Unitary Equipment	ARI	ARI 270-95
	Application of Sound Rating Levels of Outdoor Unitary Equipment	ARI	ARI 275-97
	Commercial and Industrial Unitary Air-Conditioning and Heat Pump Equipment	ARI	ARI 340/360-2004
	Methods of Testing for Rating Electrically Driven Unitary Air-Conditioning and Heat Pump Equipment	ASHRAE	ANSI/ASHRAE 37-2005
	Methods of Testing for Rating Heat-Operated Unitary Air-Conditioning and Heat Pump Equipment	ASHRAE	ANSI/ASHRAE 40-2002 (RA06)
	Methods of Testing for Rating Seasonal Efficiency of Unitary Air Conditioners and Heat Pumps	ASHRAE	ANSI/ASHRAE 116-1995 (RA05)
	Method of Testing for Rating Computer and Data Processing Room Unitary Air Conditioners	ASHRAE	ANSI/ASHRAE 127-2001
	Method of Rating Unitary Spot Air Conditioners	ASHRAE	ANSI/ASHRAE 128-2001
Ships	Specification for Mechanically Refrigerated Shipboard Air Conditioner	ASTM	ASTM F1433-97 (2004)
Accessories	Flashing and Stand Combination for Air Conditioning Units (Unit Curb)	IAPMO	IAPMO PS 120-2004
Air Conditioning	Commercial Applications Systems and Equipment, 1st ed.	ACCA	ACCA Manual CS
	Heat Pump Systems: Principles and Applications, 2nd ed.	ACCA	ACCA Manual H
	Residential Load Calculation, 8th ed.	ACCA	ANSI/ACCA Manual J
	Commercial Load Calculation, 4th ed.	ACCA	ACCA Manual N
	Comfort, Air Quality and Efficiency by Design	ACCA	ACCA Manual RS
	Environmental Systems Technology, 2nd ed. (1999)	NEBB	NEBB
	Installation of Air Conditioning and Ventilating Systems	NFPA	NFPA 90A-02

Selected Codes and Standards Published by Various Societies and Associations (*Continued*)

Subject	Title	Publisher	Reference
	Standard of Purity for Use in Mobile Air-Conditioning Systems	SAE	SAE J1991-1999
	HVAC Systems Applications, 1st ed.	SMACNA	SMACNA 1987
	HVAC Systems—Duct Design, 3rd ed.	SMACNA	SMACNA 1990
	Heating and Cooling Equipment (1995)	UL/CSA	ANSI/UL 1995/C22.2 No. 236-95
Aircraft	Air Conditioning of Aircraft Cargo	SAE	SAE AIR806B-1997
	Aircraft Fuel Weight Penalty Due to Air Conditioning	SAE	SAE AIR1168/8-1989
	Air Conditioning Systems for Subsonic Airplanes	SAE	SAE ARP85E-1991
	Environmental Control Systems Terminology	SAE	SAE ARP147E-2001
	Testing of Airplane Installed Environmental Control Systems (ECS)	SAE	SAE ARP217D-1999
	Guide for Qualification Testing of Aircraft Air Valves	SAE	SAE ARP986C-1997
	Control of Excess Humidity in Avionics Cooling	SAE	SAE ARP987A-1997
	Engine Bleed Air Systems for Aircraft	SAE	SAE ARP1796-1987
	Aircraft Ground Air Conditioning Service Connection	SAE	SAE AS4262A-1997
	Air Cycle Air Conditioning Systems for Military Air Vehicles	SAE	SAE AS4073-2000
Automotive	Refrigerant 12 Automotive Air-Conditioning Hose	SAE	SAE J51-2004
	Design Guidelines for Air Conditioning Systems for Off-Road Operator Enclosures	SAE	SAE J169-1985
	Test Method for Measuring Power Consumption of Air Conditioning and Brake Compressors for Trucks and Buses	SAE	SAE J1340-2003
	Information Relating to Duty Cycles and Average Power Requirements of Truck and Bus Engine Accessories	SAE	SAE J1343-2000
	Rating Air-Conditioner Evaporator Air Delivery and Cooling Capacities	SAE	SAE J1487-2004
	Recovery and Recycle Equipment for Mobile Automotive Air-Conditioning Systems	SAE	SAE J1990-1999
	R134a Refrigerant Automotive Air-Conditioning Hose	SAE	SAE J2064-2005
	Service Hose for Automotive Air Conditioning	SAE	SAE J2196-1997
Ships	Mechanical Refrigeration and Air-Conditioning Installations Aboard Ship	ASHRAE	ANSI/ASHRAE 26-1996 (RA06)
	Practice for Mechanical Symbols, Shipboard Heating, Ventilation, and Air Conditioning (HVAC)	ASTM	ASTM F856-97 (2004)
Air Curtains	Laboratory Methods of Testing Air Curtains for Aerodynamic Performance	AMCA	AMCA 220-05
	Air Terminals	ARI	ARI 880-98
	Standard Methods for Laboratory Airflow Measurement	ASHRAE	ANSI/ASHRAE 41.2-1987 (RA92)
	Method of Testing the Performance of Air Outlets and Inlets	ASHRAE	ANSI/ASHRAE 70-2006
	Rating the Performance of Residential Mechanical Ventilating Equipment	CSA	CAN/CSA C260-M90 (R2002)
	Air Curtains for Entranceways in Food and Food Service Establishments	NSF	NSF/ANSI 37-2005
Air Diffusion	Air Distribution Basics for Residential and Small Commercial Buildings, 1st ed.	ACCA	ACCA Manual T
	Test Code for Grilles, Registers and Diffusers	ADC	ADC 1062:GRD-84
	Method of Testing the Performance of Air Outlets and Inlets	ASHRAE	ANSI/ASHRAE 70-2006
	Method of Testing for Room Air Diffusion	ASHRAE	ANSI/ASHRAE 113-2005
Air Filters	Comfort, Air Quality, and Efficiency by Design	ACCA	ACCA Manual RS
	Industrial Ventilation: A Manual of Recommended Practice, 25th ed. (2004)	ACGIH	ACGIH
	Air Cleaners	AHAM	ANSI/AHAM AC-1-2006
	Residential Air Filter Equipment	ARI	ARI 680-2004
	Commercial and Industrial Air Filter Equipment	ARI	ARI 850-2004
	Agricultural Cabs—Engineering Control of Environmental Air Quality—Part 1: Definitions, Test Methods, and Safety Procedures	ASABE	ANSI/ASAE S525-1.2-2003
	Part 2: Pesticide Vapor Filters—Test Procedure and Performance Criteria	ASABE	ANSI/ASAE S525-2-2003
	Gravimetric and Dust-Spot Procedures for Testing Air-Cleaning Devices Used in General Ventilation for Removing Particulate Matter	ASHRAE	ANSI/ASHRAE 52.1-1992
	Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size	ASHRAE	ANSI/ASHRAE 52.2-1999
	Code on Nuclear Air and Gas Treatment	ASME	ASME AG-1-2003
	Nuclear Power Plant Air-Cleaning Units and Components	ASME	ASME N509-2002
	Testing of Nuclear Air-Treatment Systems	ASME	ASME N510-1989 (RA95)
	Specification for Filter Units, Air Conditioning: Viscous-Impingement and Dry Types, Replaceable	ASTM	ASTM F1040-87 (2001)
	Test Method for Air Cleaning Performance of a High-Efficiency Particulate Air Filter System	ASTM	ASTM F1471-93 (2001)
	Specification for Filters Used in Air or Nitrogen Systems	ASTM	ASTM F1791-00
	Method for Sodium Flame Test for Air Filters	BSI	BS 3928:1969
	Particulate Air Filters for General Ventilation: Determination of Filtration Performance	BSI	BS EN 779:2002
	Electrostatic Air Cleaners (2000)	UL	ANSI/UL 867
	High-Efficiency, Particulate, Air Filter Units (1996)	UL	ANSI/UL 586
	Air Filter Units (1994)	UL	ANSI/UL 900
	Exhaust Hoods for Commercial Cooking Equipment (1995)	UL	UL 710
	Grease Filters for Exhaust Ducts (2000)	UL	UL 1046

Selected Codes and Standards Published by Various Societies and Associations (*Continued*)

Subject	Title	Publisher	Reference
Air-Handling Units	Commercial Applications Systems and Equipment, 1st ed.	ACCA	ACCA Manual CS
	Central Station Air-Handling Units	ARI	ANSI/ARI 430-99
	Non-Recirculating Direct Gas-Fired Industrial Air Heaters	CSA	ANSI Z83.4-2003/CSA 3.7-2003
Air Leakage	Residential Duct Diagnostics and Repair (2003)	ACCA	ACCA
	Air Leakage Performance for Detached Single-Family Residential Buildings	ASHRAE	ANSI/ASHRAE 119-1988 (RA04)
	Method of Determining Air Change Rates in Detached Dwellings	ASHRAE	ANSI/ASHRAE 136-1993 (RA06)
	Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution	ASTM	ASTM E741-00
	Test Method for Field Measurement of Air Leakage Through Installed Exterior Window and Doors	ASTM	ASTM E783-93 (2002)
	Test Method for Determining Air Leakage Rate by Fan Pressurization	ASTM	ASTM E779-03
	Practices for Air Leakage Site Detection in Building Envelopes and Air Retarder Systems	ASTM	ASTM E1186-03
	Test Method for Determining the Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors Under Specified Pressure and Temperature Differences Across the Specimen	ASTM	ASTM E1424-91 (2000)
	Test Methods for Determining Airtightness of Buildings Using an Orifice Blower Door	ASTM	ASTM E1827-96 (2002)
	Practice for Determining the Effects of Temperature Cycling on Fenestration Products	ASTM	ASTM E2264-05
	Test Method for Determining Air Flow Through the Face and Sides of Exterior Windows, Curtain Walls, and Doors Under Specified Pressure Differences Across the Specimen	ASTM	ASTM E2319-04
	Test Method for Determining Air Leakage of Air Barrier Assemblies	ASTM	ASTM E2357-05
Boilers	Packaged Boiler Engineering Manual (1999)	ABMA	ABMA 100
	Selected Codes and Standards of the Boiler Industry (2001)	ABMA	ABMA 103
	Operation and Maintenance Safety Manual (1995)	ABMA	ABMA 106
	Fluidized Bed Combustion Guidelines (1995)	ABMA	ABMA 200
	Guide to Clean and Efficient Operation of Coal Stoker-Fired Boilers (2002)	ABMA	ABMA 203
	Guideline for Performance Evaluation of Heat Recovery Steam Generating Equipment (1995)	ABMA	ABMA 300
	Guidelines for Industrial Boiler Performance Improvement (1999)	ABMA	ABMA 302
	Measurement of Sound from Steam Generators (1995)	ABMA	ABMA 304
	Guideline for Gas and Oil Emission Factors for Industrial, Commercial, and Institutional Boilers (1997)	ABMA	ABMA 305
	Combustion Control Guidelines for Single Burner Firetube and Watertube Industrial/Commercial/Institutional Boilers (1999)	ABMA	ABMA 307
	Combustion Control Guidelines for Multiple-Burner Boilers (2001)	ABMA	ABMA 308
	Boiler Water Quality Requirements and Associated Steam Quality for Industrial/Commercial and Institutional Boilers (2005)	ABMA	ABMA 402
	Commercial Applications Systems and Equipment, 1st ed.	ACCA	ACCA Manual CS
	Method of Testing for Annual Fuel Utilization Efficiency of Residential Central Furnaces and Boilers	ASHRAE	ANSI/ASHRAE 103-1993
	Boiler and Pressure Vessel Code—Section I: Power Boilers; Section IV: Heating Boilers	ASME	BPVC-2004
	Fired Steam Generators	ASME	ASME PTC 4-1998
	Boiler, Pressure Vessel, and Pressure Piping Code	CSA	CSA B51-2003
	Testing Standard for Commercial Boilers	HYDI	HYDI BTS-2000
	Rating Procedure for Heating Boilers (2002)	HYDI	IBR
	Prevention of Furnace Explosions/Implosions in Multiple Burner Boilers	NFPA	ANSI /NFPA 8502-99
	Heating, Water Supply, and Power Boilers—Electric (2004)	UL	ANSI/UL 834
	Boiler and Combustion Systems Hazards Code	NFPA	NFPA 85-04
Gas or Oil	Gas-Fired Low-Pressure Steam and Hot Water Boilers	CSA	ANSI Z21.13-2004/CSA 4.9-2004
	Controls and Safety Devices for Automatically Fired Boilers	ASME	ASME CSD-1-2004
	Industrial and Commercial Gas-Fired Package Boilers	CSA	CAN 1-3.1-77 (R2001)
	Oil-Burning Equipment: Steam and Hot-Water Boilers	CSA	B140.7-2005
	Single Burner Boiler Operations	NFPA	ANSI/NFPA 8501-97
	Prevention of Furnace Explosions/Implosions in Multiple Burner Boilers	NFPA	ANSI/NFPA 8502-99
	Oil-Fired Boiler Assemblies (1995)	UL	UL 726
	Commercial-Industrial Gas Heating Equipment (1999)	UL	UL 795
	Standards and Typical Specifications for Tray Type Deaerators, 7th ed.	HEI	HEI 2003
Terminology	Ultimate Boiler Industry Lexicon: Handbook of Power Utility and Boiler Terms and Phrases, 6th ed. (2001)	ABMA	ABMA 101
Building Codes	ASTM Standards Used in Building Codes	ASTM	ASTM
	Practice for Conducting Visual Assessments for Lead Hazards in Buildings	ASTM	ASTM E2255-04
	Standard Practice for Periodic Inspection of Building Facades for Unsafe Conditions	ASTM	ASTM E2270-05
	Structural Welding Code—Steel	AWS	AWS D1.1/D1.1M:2006
	BOCA National Building Code, 14th ed. (1999)	BOCA	BNBC
	Uniform Building Code, vol. 1, 2, and 3 (1997)	ICBO	UBC V1, V2, V3

Selected Codes and Standards Published by Various Societies and Associations (*Continued*)

Subject	Title	Publisher	Reference
	International Building Code (2006)	ICC	IBC
	International Code Council Performance Code (2006)	ICC	ICC PC
	International Existing Building Code (2006)	ICC	IEBC
	International Energy Conservation Code (2006)	ICC	IECC
	International Property Maintenance Code (2006)	ICC	IPMC
	International Residential Code (2006)	ICC	IRC
	Directory of Building Codes and Regulations, State and City Volumes (annual)	NCSBCS	NCSBCS (electronic only)
	Building Construction and Safety Code	NFPA	ANSI/NFPA 5000-2006
	National Building Code of Canada (2005)	NRCC	NRCC
	Standard Building Code (1999)	SBCCI	SBC
Mechanical	Safety Code for Elevators and Escalators	ASME	ASME A17.1-2004
	Natural Gas and Propane Installation Code	CSA	CAN/CSA-B149.1-2005
	Propane Storage and Handling Code	CSA	CAN/CSA-B149.2-2005
	Uniform Mechanical Code (2006)	IAPMO	IAPMO
	International Mechanical Code (2006)	ICC	IMC
	International Fuel Gas Code (2006)	ICC	IFGC
	Standard Gas Code (1999)	SBCCI	SBC
	Standard Mechanical Code (1997)	SBCCI	SMC
Burners	Guidelines for Burner Adjustments of Commercial Oil-Fired Boilers (1996)	ABMA	ABMA 303
	Domestic Gas Conversion Burners	CSA	ANSI Z21.17-1998 (R2004)/ CSA 2.7-M98
	Installation of Domestic Gas Conversion Burners	CSA	ANSI Z21.8-1994 (R2002)
	Installation Code for Oil Burning Equipment	CSA	CAN/CSA-B139-04
	Oil-Burning Equipment: General Requirements	CSA	CAN/CSA-B140.0-03
	Vapourizing-Type Oil Burners	CSA	B140.1-1966 (R2001)
	Oil Burners: Atomizing-Type	CSA	CAN/CSA-B140.2.1-M90 (R2005)
	Pressure Atomizing Oil Burner Nozzles	CSA	B140.2.2-1971 (R2001)
	Oil Burners (2003)	UL	ANSI/UL 296
	Waste Oil-Burning Air-Heating Appliances (1995)	UL	ANSI/UL 296A
	Commercial-Industrial Gas Heating Equipment (1999)	UL	UL 795
	Commercial/Industrial Gas and/or Oil-Burning Assemblies with Emission Reduction Equipment (1999)	UL	UL 2096
Chillers	Commercial Applications Systems and Equipment, 1st ed.	ACCA	ACCA Manual CS
	Absorption Water Chilling and Water Heating Packages	ARI	ARI 560-2000
	Water Chilling Packages Using the Vapor Compression Cycle	ARI	ARI 550/590-2003
	Method of Testing Liquid-Chilling Packages	ASHRAE	ANSI/ASHRAE 30-1995
	Performance Standard for Rating Packaged Water Chillers	CSA	CAN/CSA C743-2002
Chimneys	Specification for Clay Flue Liners	ASTM	ASTM C315-02
	Specification for Industrial Chimney Lining Brick	ASTM	ASTM C980-88 (2001)
	Practice for Installing Clay Flue Lining	ASTM	ASTM C1283-03E01
	Guide for Design and Construction of Brick Liners for Industrial Chimneys	ASTM	ASTM C1298-95 (2001)
	Guide for Design, Fabrication, and Erection of Fiberglass Reinforced Plastic Chimney Liners with Coal-Fired Units	ASTM	ASTM D5364-93 (2002)
	Chimneys, Fireplaces, Vents, and Solid Fuel-Burning Appliances	NFPA	ANSI/NFPA 211-06
	Medium Heat Appliance Factory-Built Chimneys (2001)	UL	ANSI/UL 959
	Factory-Built Chimneys for Residential Type and Building Heating Appliance (2001)	UL	ANSI/UL 103
Cleanrooms	Practice for Cleaning and Maintaining Controlled Areas and Clean Rooms	ASTM	ASTM E2042-04
	Practice for Design and Construction of Aerospace Cleanrooms and Contamination Controlled Areas	ASTM	ASTM E2217-02
	Practice for Tests of Cleanroom Materials	ASTM	ASTM E2312-04
	Practice for Aerospace Cleanrooms and Associated Controlled Environments— Cleanroom Operations	ASTM	ASTM E2352-04
	Practice for Continuous Sizing and Counting of Airborne Particles in Dust-Controlled Areas and Clean Rooms Using Instruments Capable of Detecting Single Sub-Micrometre and Larger Particles	ASTM	ASTM F50-92 (2001)E01
	Test Method for Sizing and Counting Airborne Particulate Contamination in Clean Rooms and Other Dust-Controlled Areas Designed for Electronic and Similar Applications	ASTM	ASTM F25-04
	Procedural Standards for Certified Testing of Cleanrooms, 2nd ed. (1996)	NEBB	NEBB
Coils	Forced-Circulation Air-Cooling and Air-Heating Coils	ARI	ARI 410-2001
	Methods of Testing Forced Circulation Air Cooling and Air Heating Coils	ASHRAE	ANSI/ASHRAE 33-2000
Comfort Conditions	Threshold Limit Values for Physical Agents (updated annually)	ACGIH	ACGIH
	Good HVAC Practices for Residential and Commercial Buildings (2003)	ACCA	ACCA
	Comfort, Air Quality and Efficiency by Design (1997)	ACCA	ACCA Manual RS

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Subject	Title	Publisher	Reference
	Thermal Environmental Conditions for Human Occupancy	ASHRAE	ANSI/ASHRAE 55-2004
	Classification for Serviceability of an Office Facility for Thermal Environment and Indoor Air Conditions	ASTM	ASTM E2320-04
	Hot Environments—Estimation of the Heat Stress on Working Man, Based on the WBGT Index (Wet Bulb Globe Temperature)	ISO	ISO 7243:1989
	Ergonomics of the Thermal Environment—Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria	ISO	ISO 7730:2005
	Ergonomics of the Thermal Environment—Determination of Metabolic Rate	ISO	ISO 8996:2004
	Ergonomics of the Thermal Environment—Estimation of the Thermal Insulation and Evaporative Resistance of a Clothing Ensemble	ISO	ISO 9920:1995
Compressors	Safety Standard for Air Compressor Systems	ASME	ASME B19.1-1995
	Safety Standard for Compressors for Process Industries	ASME	ASME B19.3-1991
	Displacement Compressors, Vacuum Pumps and Blowers	ASME	ASME PTC 9-1970 (RA97)
	Performance Test Code on Compressors and Exhausters	ASME	ASME PTC 10-1997 (RA03)
	Compressed Air and Gas Handbook, 6th ed. (2003)	CAGI	CAGI
Refrigerant	Variable Capacity Positive Displacement Refrigerant Compressors and Compressor Units for Air-Conditioning and Heat Pump Applications	ARI	ANSI/ARI 500-2000
	Positive Displacement Condensing Units	ARI	ARI 520-2004
	Positive Displacement Refrigerant Compressors and Compressor Units	ARI	ARI 540-2004
	Safety Standard for Refrigeration Systems	ASHRAE	ANSI/ASHRAE 15-2004
	Methods of Testing for Rating Positive Displacement Refrigerant Compressors and Condensing Units	ASHRAE	ANSI/ASHRAE 23-2005
	Testing of Refrigerant Compressors	ISO	ISO 917:1989
	Refrigerant Compressors—Presentation of Performance Data	ISO	ISO 9309:1989
	Hermetic Refrigerant Motor-Compressors (1996)	UL/CSA	UL 984/C22.2 No.140.2-96 (R2001)
Computers	Method of Rating Computer and Data Processing Room Unitary Air Conditioners	ASHRAE	ANSI/ASHRAE 127-2001
	Method of Test for the Evaluation of Building Energy Analysis Computer Programs	ASHRAE	ANSI/ASHRAE 140-2004
	Protection of Electronic Computer/Data Processing Equipment	NFPA	NFPA 75-03
Condensers	Commercial Applications Systems and Equipment, 1st ed.	ACCA	ACCA Manual CS
	Water-Cooled Refrigerant Condensers, Remote Type	ARI	ARI 450-99
	Remote Mechanical-Draft Air-Cooled Refrigerant Condensers	ARI	ARI 460-2005
	Remote Mechanical Draft Evaporative Refrigerant Condensers	ARI	ARI 490-2003
	Safety Standard for Refrigeration Systems	ASHRAE	ANSI/ASHRAE 15-2004
	Method of Testing for Rating Remote Mechanical-Draft Air-Cooled Refrigerant Condensers	ASHRAE	ANSI/ASHRAE 20-1997 (RA06)
	Methods of Testing for Rating Water-Cooled Refrigerant Condensers	ASHRAE	ANSI/ASHRAE 22-2003
	Methods of Laboratory Testing Remote Mechanical-Draft Evaporative Refrigerant Condensers	ASHRAE	ANSI/ASHRAE 64-2005
	Steam Surface Condensers	ASME	ASME PTC 12.2-1998
	Standards for Steam Surface Condensers, 9th ed., Addendum 1	HEI	HEI 2002
	Standards for Direct Contact Barometric and Low Level Condensers, 7th ed.	HEI	HEI 2004
	Refrigerant-Containing Components and Accessories, Nonelectrical (2001)	UL	ANSI/UL 207
Condensing Units	Commercial Applications Systems and Equipment	ACCA	ACCA Manual CS
	Commercial and Industrial Unitary Air-Conditioning Condensing Units	ARI	ARI 365-2002
	Methods of Testing for Rating Positive Displacement Refrigerant Compressors and Condensing Units	ASHRAE	ANSI/ASHRAE 23-2005
	Heating and Cooling Equipment (2005)	UL/CSA	ANSI/UL 1995/C22.2 No. 236-95
Containers	Series 1 Freight Containers—Classifications, Dimensions, and Ratings	ISO	ISO 668:1995
	Series 1 Freight Containers—Specifications and Testing; Part 2: Thermal Containers	ISO	ISO 1496-2:1996
	Animal Environment in Cargo Compartments	SAE	SAE AIR1600A-1997
Controls	Temperature Control Systems (2002)	AABC	National Standards, Ch. 12
	BACnet®—A Data Communication Protocol for Building Automation and Control Networks	ASHRAE	ANSI/ASHRAE 135-2004
	Method of Test for Conformance to BACnet®	ASHRAE	ANSI/ASHRAE 135.1-2003
	Temperature-Indicating and Regulating Equipment	CSA	C22.2 No. 24-93 (R2003)
	Performance Requirements for Electric Heating Line-Voltage Wall Thermostats	CSA	C273.4-M1978 (R2003)
	Performance Requirements for Thermostats Used with Individual Room Electric Space Heating Devices	CSA	CAN/CSA C828-99 (R2005)
	Solid-State Controls for Appliances (2003)	UL	UL 244A
	Limit Controls (1994)	UL	ANSI/UL 353
	Primary Safety Controls for Gas- and Oil-Fired Appliances (1994)	UL	ANSI/UL 372
	Temperature-Indicating and -Regulating Equipment (1994)	UL	UL 873
	Tests for Safety-Related Controls Employing Solid-State Devices (2004)	UL	UL 991

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Subject	Title	Publisher	Reference
	Control Centers for Changing Message Type Electric Signals (2003)	UL	UL 1433
	Automatic Electrical Controls for Household and Similar Use; Part 1: General Requirements (2002)	UL	UL 60730-1A
	Process Control Equipment (2002)	UL	UL 61010C-1
Commercial and Industrial	Guidelines for Boiler Control Systems (Gas/Oil Fired Boilers) (1998)	ABMA	ABMA 301
	Guideline for the Integration of Boilers and Automated Control Systems in Heating Applications (1998)	ABMA	ABMA 306
	Industrial Control and Systems: General Requirements	NEMA	NEMA ICS 1-2000 (R2005)
	Preventive Maintenance of Industrial Control and Systems Equipment	NEMA	NEMA ICS 1.3-1986 (R2005)
	Industrial Control and Systems, Controllers, Contactors, and Overload Relays Rated Not More than 2000 Volts AC or 750 Volts DC	NEMA	NEMA ICS 2-2000 (R2005)
	Industrial Control and Systems: Instructions for the Handling, Installation, Operation and Maintenance of Motor Control Centers Rated Not More than 600 Volts	NEMA	NEMA ICS 2.3-1995 (R2002)
	Industrial Control Equipment (1999)	UL	ANSI/UL 508
Residential	Manually Operated Gas Valves for Appliances, Appliance Connector Valves and Hose End Valves	CSA	ANSI Z21.15-1997 (R03)/CGA 9.1-1997
	Gas Appliance Pressure Regulators	CSA	ANSI Z21.18-2000/CSA 6.3-2000
	Automatic Gas Ignition Systems and Components	CSA	ANSI Z21.20-2005
	Gas Appliance Thermostats	CSA	ANSI Z21.23-2000
	Manually-Operated Piezo-Electric Spark Gas Ignition Systems and Components	CSA	ANSI Z21.77-2005/CGA 6.23-2005
	Manually Operated Electric Gas Ignition Systems and Components	CSA	ANSI Z21.92-2001/CSA 6.29-2001
	Residential Controls—Electrical Wall-Mounted Room Thermostats	NEMA	NEMA DC 3-2003
	Residential Controls—Surface Type Controls for Electric Storage Water Heaters	NEMA	NEMA DC 5-2002
	Residential Controls—Temperature Limit Controls for Electric Baseboard Heaters	NEMA	NEMA DC 10-1983 (R2003)
	Hot-Water Immersion Controls	NEMA	NEMA DC 12-1985 (R2002))
	Line-Voltage Integrally Mounted Thermostats for Electric Heaters	NEMA	NEMA DC 13-1979 (R2002)
	Residential Controls—Class 2 Transformers	NEMA	NEMA DC 20-1992 (R2003)
	Safety Guidelines for the Application, Installation, and Maintenance of Solid State Controls	NEMA	NEMA ICS 1.1-1984 (R2003)
	Electrical Quick-Connect Terminals (2003)	UL	ANSI/UL 310
Coolers	Refrigeration Equipment	CSA	CAN/CSA-C22.2 No. 120-M91 (R2004)
	Unit Coolers for Refrigeration	ARI	ARI 420-2000
	Refrigeration Unit Coolers (2004)	UL	ANSI/UL 412
Air	Methods of Testing Forced Convection and Natural Convection Air Coolers for Refrigeration	ASHRAE	ANSI/ASHRAE 25-2001 (RA06)
Drinking Water	Self-Contained, Mechanically Refrigerated Drinking-Water Coolers	ARI	ARI 1010-2002
	Methods of Testing for Rating Drinking-Water Coolers with Self-Contained Mechanical Refrigeration	ASHRAE	ANSI/ASHRAE 18-2006
	Drinking-Water Coolers (1993)	UL	ANSI/UL 399
	Drinking Water System Components—Health Effects	NSF	NSF/ANSI 61-2005
Evaporative	Method of Testing Direct Evaporative Air Coolers	ASHRAE	ANSI/ASHRAE 133-2001
	Method of Test for Rating Indirect Evaporative Coolers	ASHRAE	ANSI/ASHRAE 143-2000
Food and Beverage	Terminology for Milking Machines, Milk Cooling, and Bulk Milk Handling Equipment	ASABE	ASAE S300.3-2003
	Methods of Testing for Rating Vending Machines for Bottled, Canned, and Other Sealed Beverages	ASHRAE	ANSI/ASHRAE 32.1-2004
	Methods of Testing for Rating Pre-Mix and Post-Mix Beverage Dispensing Equipment	ASHRAE	ANSI/ASHRAE 32.2-2003
	Manual Food and Beverage Dispensing Equipment	NSF	NSF/ANSI 18-2005
	Commercial Bulk Milk Dispensing Equipment	NSF	NSF/ANSI 20-2000
	Refrigerated Vending Machines (1995)	UL	ANSI/UL 541
Liquid	Refrigerant-Cooled Liquid Coolers, Remote Type	ARI	ARI 480-2001
	Methods of Testing for Rating Liquid Coolers	ASHRAE	ANSI/ASHRAE 24-2000 (RA05)
	Liquid Cooling Systems	SAE	SAE AIR1811A-1997
Cooling Towers	Cooling Tower Testing (2002)	AABC	National Standards, Ch 13
	Commercial Applications, Systems, and Equipment, 1st ed.	ACCA	ACCA Manual CS
	Bioaerosols: Assessment and Control (1999)	ACGIH	ACGIH
	Atmospheric Water Cooling Equipment	ASME	ASME PTC 23-2003
	Water-Cooling Towers	NFPA	NFPA 214-05
	Acceptance Test Code for Water Cooling Towers	CTI	CTI ATC-105 (00)
	Code for Measurement of Sound from Water Cooling Towers (2005)	CTI	CTI ATC-128 (05)
	Acceptance Test Code for Spray Cooling Systems (1985)	CTI	CTI ATC-133 (85)
	Nomenclature for Industrial Water Cooling Towers (1997)	CTI	CTI NCL-109 (97)
	Recommended Practice for Airflow Testing of Cooling Towers (1994)	CTI	CTI PFM-143 (94)
	Fiberglass-Reinforced Plastic Panels (2002)	CTI	CTI STD-131 (02)
	Certification of Water Cooling Tower Thermal Performance (R2004)	CTI	CTI STD-201 (02)
Crop Drying	Density, Specific Gravity, and Mass-Moisture Relationships of Grain for Storage	ASABE	ANSI/ASAE D241.4-2003
	Dielectric Properties of Grain and Seed	ASABE	ASAE D293.2-1989 (R2005)
	Shelled Corn Storage Time for 0.5% Dry Matter Loss	ASABE	ASAE D535-2005

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Subject	Title	Publisher	Reference
	Thermal Properties of Grain and Grain Products	ASABE	ASAE D243.4-2003
	Moisture Relationships of Plant-Based Agricultural Products	ASABE	ASAE D245.5-19995 (R2001)
	Construction and Rating of Equipment for Drying Farm Crops	ASABE	ASAE S248.3-1976 (R2005)
	Cubes, Pellets, and Crumbles—Definitions and Methods for Determining Density, Durability, and Moisture Content	ASABE	ASAE S269.4-2001
	Resistance to Airflow of Grains, Seeds, Other Agricultural Products, and Perforated Metal Sheets	ASABE	ASAE D272.3-2001
	Moisture Measurement—Unground Grain and Seeds	ASABE	ASAE S352.2-2003
	Moisture Measurement—Meat and Meat Products	ASABE	ASAE S353-2003
	Moisture Measurement—Forages	ASABE	ASAE S358.2-2003
	Moisture Measurement—Peanuts	ASABE	ASAE S410.1-2003
	Energy Efficiency Test Procedure for Tobacco Curing Structures	ASABE	ASAE S416-2003
	Thin-Layer Drying of Agricultural Crops	ASABE	ANSI/ASAE S448.1-2001 (R2006)
	Moisture Measurement—Tobacco	ASABE	ASAE S487-2003
	Thin-Layer Drying of Agricultural Crops	ASABE	ASAE S488-1990 (R2005)
	Temperature Sensor Locations for Seed-Cotton Drying Systems	ASABE	ASAE S530-2001
Dehumidifiers	Commercial Applications, Systems, and Equipment, 1st ed.	ACCA	ACCA Manual CS
	Bioaerosols: Assessment and Control (1999)	ACGIH	ACGIH
	Dehumidifiers	AHAM	ANSI/AHAM DH-1-2003
	Testing for Rating Desiccant Dehumidifiers Utilizing Heat for the Regeneration Process	ASHRAE	ANSI/ASHRAE 139-1998
	Moisture Separator Reheaters	ASME	PTC 12.4-1992 (RA04)
	Dehumidifiers	CSA	C22.2 No. 92-1971 (R2004)
	Performance of Dehumidifiers	CSA	CAN/CSA C749-94 (R2005)
	Dehumidifiers (2004)	UL	ANSI/UL 474
Desiccants	Method of Testing Desiccants for Refrigerant Drying	ASHRAE	ANSI/ASHRAE 35-1992
Documentation	Preparation of Operating and Maintenance Documentation for Building Systems	ASHRAE	ASHRAE *Guideline* 4-1993
Driers	Liquid-Line Driers	ARI	ANSI/ARI 710-2004
	Method of Testing Liquid Line Refrigerant Driers	ASHRAE	ANSI/ASHRAE 63.1-1995 (RA01)
	Refrigerant-Containing Components and Accessories, Nonelectrical (2001)	UL	ANSI/UL 207
Ducts and Fittings	Hose, Air Duct, Flexible Nonmetallic, Aircraft	SAE	SAE AS1501C-1994
	Ducted Electric Heat Guide for Air Handling Systems, 2nd ed.	SMACNA	SMACNA 1994
	Factory-Made Air Ducts and Air Connectors (2005)	UL	ANSI/UL 181
Construction	Industrial Ventilation: A Manual of Recommended Practice, 25th ed. (2004)	ACGIH	ACGIH
	Preferred Metric Sizes for Flat, Round, Square, Rectangular, and Hexagonal Metal Products	ASME	ASME B32.100-2005
	Sheet Metal Welding Code	AWS	AWS D9.1:2000
	Fibrous Glass Duct Construction Standards, 5th ed.	NAIMA	NAIMA AH116
	Residential Fibrous Glass Duct Construction Standards, 3rd ed.	NAIMA	NAIMA AH119
	Fibrous Glass Duct Construction with 1-1/2″ Duct Boards	NAIMA	NAIMA AH120
	Thermoplastic Duct (PVC) Construction Manual, 2nd ed.	SMACNA	SMACNA 1995
	Accepted Industry Practices for Sheet Metal Lagging, 1st ed.	SMACNA	SMACNA 2002
	Fibrous Glass Duct Construction Standards, 7th ed.	SMACNA	SMACNA 2003
	HVAC Duct Construction Standards, Metal and Flexible, 3rd ed.	SMACNA	SMACNA 2005
	Rectangular Industrial Duct Construction Standards, 2nd ed.	SMACNA	SMACNA 2004
	Round Industrial Duct Construction Standards, 2nd ed.	SMACNA	ANSI/SMACNA 005-2003
Industrial	Round Industrial Duct Construction Standards, 2nd ed.	SMACNA	SMACNA 1999
	Rectangular Industrial Duct Construction Standards, 2nd ed.	SMACNA	SMACNA 2004
Installation	Flexible Duct Performance and Installation Standards, 4th ed.	ADC	ADC-91
	Installation of Air Conditioning and Ventilating Systems	NFPA	NFPA 90A-02
	Installation of Warm Air Heating and Air-Conditioning Systems	NFPA	NFPA 90B-06
Material Specifica-tions	Specification for General Requirements for Flat-Rolled Stainless and Heat-Resisting Steel Plate, Sheet and Strip	ASTM	ASTM A480/A480M-05
	Specification for General Requirements for Steel, Sheet, Carbon, and High-Strength, Low-Alloy, Hot-Rolled and Cold-Rolled	ASTM	ASTM A568/A568M-05a
	Specification for Steel Sheet, Zinc-Coated (Galvanized) or Zinc-Iron Alloy-Coated (Galvannealed) by the Hot-Dipped Process	ASTM	ASTM A653/A653M-05a
	Specification for General Requirements for Steel Sheet, Metallic-Coated by the Hot-Dip Process	ASTM	ASTM A924/A924M-04
	Specification for Steel, Sheet and Strip, Cold-Rolled, Carbon, Structural, High-Strength Low-Alloy and High-Strength Low-Alloy with Improved Formability	ASTM	ASTM A1008-05b
	Specification for Steel, Sheet and Strip, Hot-Rolled, Carbon, Structural, High-Strength Low-Alloy and High-Strength Low-Alloy with Improved Formability	ASTM	ASTM A1011/A1011M-05a
	Practice for Measuring Flatness Characteristics of Coated Sheet Products	ASTM	ASTM A1030-05
System Design	Installation Techniques for Perimeter Heating and Cooling, 11th ed.	ACCA	ACCA Manual 4
	Residential Duct Systems	ACCA	ANSI/ACCA Manual D
	Commercial Low Pressure, Low Velocity Duct System Design, 1st ed.	ACCA	ACCA Manual Q

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Subject	Title	Publisher	Reference
Testing	Air Distribution Basics for Residential and Small Commercial Buildings, 1st ed.	ACCA	ACCA Manual T
	Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems	ASHRAE	ANSI/ASHRAE 152-2004
	Closure Systems for Use with Rigid Air Ducts (2005)	UL	ANSI/UL 181A
	Closure Systems for Use with Flexible Air Ducts and Air Connectors (2005)	UL	ANSI/UL 181B
	Duct Leakage Testing (2002)	AABC	National Standards, Ch 5
	Residential Duct Diagnostics and Repair (2003)	ACCA	ACCA
	Flexible Air Duct Test Code	ADC	ADC FD-72 (R1979)
	Test Method for Measuring Acoustical and Airflow Performance of Duct Liner Materials and Prefabricated Silencers	ASTM	ASTM E477-05
	Method of Testing to Determine Flow Resistance of HVAC Ducts and Fittings	ASHRAE	ANSI/ASHRAE 120-1999
	Method of Testing HVAC Air Ducts	ASHRAE	ANSI/ASHRAE/SMACNA 126-2000
	HVAC Air Duct Leakage Test Manual, 1st ed.	SMACNA	SMACNA 1985
	HVAC Duct Systems Inspection Guide, 3rd ed.	SMACNA	SMACNA 2005
Electrical	Electrical Power Systems and Equipment—Voltage Ratings	ANSI	ANSI C84.1-2001
	Test Method for Bond Strength of Electrical Insulating Varnishes by the Helical Coil Test	ASTM	ASTM D2519-02
	Standard Specification for Shelter, Electrical Equipment, Lightweight	ASTM	ASTM E2377-04
	Canadian Electrical Code, Part I (20th ed.)	CSA	C22.1-2006
	Part II—General Requirements	CSA	CAN/CSA-C22.2 No.0-M91 (R2001)
	ICC Electrical Code, Administrative Provisions (2006)	ICC	ICCEC
	Enclosures for Electrical Equipment (1000 Volts Maximum)	NEMA	ANSI/NEMA 250-2003
	Molded Case Circuit Breakers and Molded Case Switches	NEMA	NEMA AB 1-2002
	Low Voltage Cartridge Fuses	NEMA	NEMA FU 1-2002
	Industrial Control and Systems: Terminal Blocks	NEMA	NEMA ICS 4-2005
	Industrial Control and Systems: Enclosures	NEMA	ANSI/NEMA ICS 6-1993 (R2001)
	Application Guide for Ground Fault Protective Devices for Equipment	NEMA	ANSI/NEMA PB 2.2-2004
	General Color Requirements for Wiring Devices	NEMA	NEMA WD 1-1999 (R2005)
	Wiring Devices—Dimensional	NEMA	ANSI/NEMA WD 6-2002
	National Electrical Code	NFPA	NFPA 70-05
	National Fire Alarm Code	NFPA	NFPA 72-02
	Compatibility of Electrical Connectors and Wiring	SAE	SAE AIR1329A-1988
Energy	Air-Conditioning and Refrigerating Equipment Nameplate Voltages	ARI	ARI 110-2002
	Comfort, Air Quality and Efficiency by Design	ACCA	ACCA Manual RS
	Energy Standard for Buildings Except Low-Rise Residential Buildings	ASHRAE	ANSI/ASHRAE/IESNA 90.1-2004
	Energy-Efficient Design of Low-Rise Residential Buildings	ASHRAE	ANSI/ASHRAE/IESNA 90.2-2004
	Energy Conservation in Existing Buildings	ASHRAE	ANSI/ASHRAE/IESNA 100-2006
	Standard Methods of Measuring and Expressing Building Energy Performance	ASHRAE	ANSI/ASHRAE 105-1984 (RA99)
	Method of Test for the Evaluation of Building Energy Analysis Computer Programs	ASHRAE	ANSI/ASHRAE 140-2004
	Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems	ASHRAE	ANSI/ASHRAE 152-2004
	Fuel Cell Power Systems Performance	ASME	PTC 50-2002
	International Energy Conservation Code (2006)	ICC	IECC
	Uniform Solar Energy Code (2000)	IAPMO	IAPMO
	Model Energy Code, Thermal Envelope Compliance Guide for One and Two Family Dwellings	NAIMA	NAIMA BI407
	Energy Management Guide for Selection and Use of Fixed Frequency Medium AC Squirrel-Cage Polyphase Induction Motors	NEMA	NEMA MG 10-2001
	Energy Management Guide for Selection and Use of Single-Phase Motors	NEMA	NEMA MG 11-1977 (R2001)
	HVAC Systems Commissioning Manual, 1st ed.	SMACNA	SMACNA 1994
	Building Systems Analysis and Retrofit Manual, 1st ed.	SMACNA	SMACNA 1995
	Energy Systems Analysis and Management, 1st ed.	SMACNA	SMACNA 1997
	Energy Management Equipment (1998)	UL	UL 916
Exhaust Systems	Fan Systems: Supply/Return/Relief/Exhaust (2002)	AABC	National Standards, Ch 10
	Commercial Applications, Systems, and Equipment, 1st ed.	ACCA	ACCA Manual CS
	Industrial Ventilation: A Manual of Recommended Practice, 25th ed. (2004)	ACGIH	ACGIH
	Fundamentals Governing the Design and Operation of Local Exhaust Ventilation Systems	AIHA	ANSI/AIHA Z9.2-2001
	Safety Code for Design, Construction, and Ventilation of Spray Finishing Operations	AIHA	ANSI/AIHA Z9.3-1994
	Abrasive Blasting Operations—Ventilation and Safe Practices	AIHA	ANSI/AIHA Z9.4-1997
	Laboratory Ventilation	AIHA	ANSI/AIHA Z9.5-2003
	Exhaust Systems for Grinding, Polishing, and Buffing	AIHA	ANSI/AIHA Z9.6-1999
	Recirculation of Air from Industrial Process Exhaust Systems	AIHA	ANSI/AIHA Z9.7-1998
	Method of Testing Performance of Laboratory Fume Hoods	ASHRAE	ANSI/ASHRAE 110-1995
	Ventilation for Commercial Cooking Operations	ASHRAE	ANSI/ASHRAE 154-2003

Selected Codes and Standards Published by Various Societies and Associations (*Continued*)

Subject	Title	Publisher	Reference
	Performance Test Code on Compressors and Exhausters	ASME	PTC 10-1997 (RA03)
	Flue and Exhaust Gas Analyses	ASME	PTC 19.10-1981
	Mechanical Flue-Gas Exhausters	CSA	CAN 3-B255-M81 (R2005)
	Exhaust Systems for Air Conveying of Vapors, Gases, Mists, and Noncombustible Particulate Solids	NFPA	ANSI/NFPA 91-04
	Draft Equipment (1993)	UL	UL 378
Expansion Valves	Thermostatic Refrigerant Expansion Valves	ARI	ANSI/ARI 750-2001
	Method of Testing Capacity of Thermostatic Refrigerant Expansion Valves	ASHRAE	ANSI/ASHRAE 17-1998 (RA03)
Fan-Coil Units	Industrial Ventilation: A Manual of Recommended Practice, 25th ed. (2004)	ACGIH	ACGIH
	Room Fan-Coils	ARI	ARI 440-2005
	Methods of Testing for Rating Fan-Coil Conditioners	ASHRAE	ANSI/ASHRAE 79-2002 (RA06)
	Heating and Cooling Equipment (2005)	UL/CSA	ANSI/UL 1995/C22.2 No. 236-95
Fans	Residential Duct Systems	ACCA	ANSI/ACCA Manual D
	Commercial Low Pressure, Low Velocity Duct System Design, 1st ed.	ACCA	ACCA Manual Q
	Industrial Ventilation: A Manual of Recommended Practice, 25th ed. (2004)	ACGIH	ACGIH
	Standards Handbook	AMCA	AMCA 99-03
	Drive Arrangements for Centrifugal Fans	AMCA	ANSIAMCA 99-2404-03
	Inlet Box Positions for Centrifugal Fans	AMCA	ANSI/AMCA 99-2405-03
	Designation for Rotation and Discharge of Centrifugal Fans	AMCA	ANSI/AMCA 99-2406-03
	Motor Positions for Belt or Chain Drive Centrifugal Fans	AMCA	ANSI/AMCA 99-2407-03
	Operating Limits for Centrifugal Fans	AMCA	AMCA 99-2408-69
	Drive Arrangements for Tubular Centrifugal Fans	AMCA	ANSI/AMCA 99-2410-03
	Impeller Diameters and Outlet Areas for Centrifugal Fans	AMCA	ANSI/AMCA 99-2412-03
	Impeller Diameters and Outlet Areas for Industrial Centrifugal Fans	AMCA	ANSI/AMCA 99-2413-03
	Impeller Diameters and Outlet Areas for Tubular Centrifugal Fans	AMCA	ANSI/AMCA 99-2414-03
	Dimensions for Axial Fans	AMCA	ANSI/AMCA 99-3001-03
	Drive Arrangements for Axial Fans	AMCA	ANSI/AMCA 99-3404-03
	Air Systems	AMCA	AMCA 200-95
	Fans and Systems	AMCA	AMCA 201-02
	Troubleshooting	AMCA	AMCA 202-98
	Field Performance Measurement of Fan Systems	AMCA	AMCA 203-90
	Balance Quality and Vibration Levels for Fans	AMCA	ANSI/AMCA 204-05
	Laboratory Methods of Testing Air Circulator Fans for Rating	AMCA	ANSI/AMCA 230-99
	Laboratory Method of Testing Positive Pressure Ventilators for Rating	AMCA	ANSI/AMCA 240-96
	Reverberant Room Method for Sound Testing of Fans	AMCA	AMCA 300-05
	Methods for Calculating Fan Sound Ratings from Laboratory Test Data	AMCA	AMCA 301-05
	Application of Sone Ratings for Non-Ducted Air Moving Devices	AMCA	AMCA 302-73
	Application of Sound Power Level Ratings for Fans	AMCA	AMCA 303-79
	Recommended Safety Practices for Users and Installers of Industrial and Commercial Fans	AMCA	AMCA 410-96
	Industrial Process/Power Generation Fans: Site Performance Test Standard	AMCA	AMCA 803-02
	Mechanical Balance of Fans and Blowers	ARI	ARI *Guideline* G-2002
	Acoustics—Measurement of Noise and Vibration of Small Air-Moving Devices—Part 1: Airborne Noise Emission	ASA	ANSI S12.11-2003/Part 1/ISO 10302:1996 (MOD)
	Part 2: Structure-Borne Vibration	ASA	ANSI S12.11-2003/Part 2
	Laboratory Methods of Testing Fans for Aerodynamic Performance Rating	ASHRAE/ AMCA	ANSI/ASHRAE 51-1999 ANSI/AMCA 210-99
	Laboratory Method of Testing to Determine the Sound Power in a Duct	ASHRAE/ AMCA	ANSI/ASHRAE 68-1997 ANSI/AMCA 330-97
	Methods of Testing Fan Vibration—Blade Vibrations and Critical Speeds	ASHRAE	ANSI/ASHRAE 87.1-1992
	Laboratory Methods of Testing Fans Used to Exhaust Smoke in Smoke Management Systems	ASHRAE	ANSI/ASHRAE 149-2000 (RA05)
	Ventilation for Commercial Cooking Operations	ASHRAE	ANSI/ASHRAE 154-2003
	Fans	ASME	ANSI/ASME PTC 11-1984 (RA03)
	Fans and Ventilators	CSA	C22.2 No. 113-M1984 (R2004)
	Rating the Performance of Residential Mechanical Ventilating Equipment	CSA	CAN/CSA C260-M90 (R2002)
	Energy Performance of Ceiling Fans	CSA	CAN/CSA C814-96 (R2001)
	Electric Fans (1999)	UL	ANSI/UL 507
	Power Ventilators (2004)	UL	ANSI/UL 705
Fenestration	Test Method for Accelerated Weathering of Sealed Insulating Glass Units	ASTM	ASTM E773-01
	Specification for Classification of the Durability of Sealed Insulating Glass Units	ASTM	ASTM E774-97
	Practice for Calculation of Photometric Transmittance and Reflectance of Materials to Solar Radiation	ASTM	ASTM E971-88 (2003)
	Test Method for Solar Photometric Transmittance of Sheet Materials Using Sunlight	ASTM	ASTM E972-96 (2002)
	Test Method for Solar Transmittance (Terrestrial) of Sheet Materials Using Sunlight	ASTM	ASTM E1084-86 (2003)
	Practice for Determining the Load Resistance of Glass in Buildings	ASTM	ASTM E1300-04 E01

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Subject	Title	Publisher	Reference
	Practice for Installation of Exterior Windows, Doors and Skylights	ASTM	ASTM E2112-01
	Test Method for Insulating Glass Unit Performance	ASTM	ASTM E2188-02
	Test Method for Testing Resistance to Fogging Insulating Glass Units	ASTM	ASTM E2189-02
	Specification for Insulating Glass Unit Performance and Evaluation	ASTM	ASTM E2190-02
	Guide for Assessing the Durability of Absorptive Electrochemical Coatings within Sealed Insulating Glass Units	ASTM	ASTM E2354-04
	Tables for Reference Solar Spectral Irradiance: Direct Normal and Hemispherical on 37° Tilted Surface	ASTM	ASTM G173-03
	Windows	CSA	A440-00
	Energy Performance Evaluation of Windows and Other Fenestration Systems	CSA	A440.2-04
	Window and Door Installation	CSA	A440.4-98
	Energy Performance Evaluation of Swinging Doors	CSA	A453-95 (R2000)
Filter-Driers	Flow-Capacity Rating of Suction-Line Filters and Suction-Line Filter-Driers	ARI	ARI 730-2005
	Method of Testing Liquid Line Filter-Drier Filtration Capability	ASHRAE	ANSI/ASHRAE 63.2-1996 (RA06)
	Method of Testing Flow Capacity of Suction Line Filters and Filter-Driers	ASHRAE	ANSI/ASHRAE 78-1985 (RA03)
Fireplaces	Factory-Built Fireplaces (1996)	UL	ANSI/UL 127
	Fireplace Stoves (1996)	UL	UL 737
Fire Protection	Test Method for Surface Burning Characteristics of Building Materials	ASTM/NFPA	ASTM E84-05e1/NFPA 255-06
	Test Methods for Fire Test of Building Construction and Materials	ASTM	ASTM E119-05a
	Test Method for Room Fire Test of Wall and Ceiling Materials and Assemblies	ASTM	ASTM E2257-03
	Test Method for Determining Fire Resistance of Perimeter Fire Barriers Using Intermediate-Scale Multi-Story Test Apparatus	ASTM	ASTM E2307-04e01
	Guide for Laboratory Monitors	ASTM	ASTM E2335-04
	Test Method for Fire Resistance Grease Duct Enclosure Systems	ASTM	ASTM E2336-04
	Practice for Specimen Preparation and Mounting of Paper or Vinyl Wall Coverings to Assess Surface Burning Characteristics	ASTM	ASTM E2404-05
	BOCA National Fire Prevention Code, 11th ed. (1999)	BOCA	BNFPC
	Uniform Fire Code	IFCI	UPC 1997
	International Fire Code (2006)	ICC	IFC
	International Mechanical Code (2006)	ICC	IMC
	International Urban-Wildland Interface Code (2006)	ICC	IUWIC
	Fire-Resistance Tests—Elements of Building Construction; Part 1: Gen. Requirements	ISO	ISO 834-1:1999
	Fire-Resistance Tests—Door and Shutter Assemblies	ISO	ISO 3008:1976
	Reaction to Fire Tests—Ignitability of Building Products Using a Radiant Heat Source	ISO	ISO 5657:1997
	Fire-Resistance Tests—Ventilating Ducts	ISO	ISO 6944:1985
	Fire Service Annunciator and Interface	NEMA	NEMA SB 30-2005
	Fire Protection Handbook (2003)	NFPA	NFPA
	National Fire Codes (issued annually)	NFPA	NFPA
	Fire Protection Guide to Hazardous Materials	NFPA	NFPA HAZ-01
	Uniform Fire Code	NFPA	NFPA 1-06
	Installation of Sprinkler Systems	NFPA	NFPA 13-2002
	Fire Protection for Laboratories Using Chemicals	NFPA	NFPA 45-04
	Flammable and Combustible Liquids Code	NFPA	NFPA 30-03
	National Fire Alarm Code	NFPA	NFPA 72-02
	Fire Doors and Fire Windows	NFPA	NFPA 80-99
	Health Care Facilities	NFPA	NFPA 99-05
	Life Safety Code	NFPA	NFPA 101-06
	Methods of Fire Tests of Door Assemblies	NFPA	NFPA 252-03
	Standard Fire Prevention Code (1999)	SBCCI	SFPC
	Fire, Smoke and Radiation Damper Installation Guide for HVAC Systems, 5th ed.	SMACNA	SMACNA 2002
	Fire Tests of Door Assemblies (1997)	UL	ANSI/UL 10B
	Heat Responsive Links for Fire-Protection Service (2003)	UL	ANSI/UL 33
	Fire Tests of Building Construction and Materials (2003)	UL	ANSI/UL 263
	Fire Dampers (1999)	UL	ANSI/UL 555
	Fire Tests of Through-Penetration Firestops (2003)	UL	ANSI/UL 1479
Smoke Management	Commissioning Smoke Management Systems	ASHRAE	ASHRAE *Guideline* 5-1994 (RA01)
	Laboratory Methods of Testing Fans Used to Exhaust Smoke in Smoke Management Systems	ASHRAE	ANSI/ASHRAE 149-2000 (RA05)
	Recommended Practice for Smoke-Control Systems	NFPA	NFPA 92A-06
	Smoke Management Systems in Malls, Atria, and Large Areas	NFPA	NFPA 92B-05
	Ceiling Dampers (1996)	UL	UL 555C
	Smoke Dampers (1999)	UL	UL 555S
Freezers	Energy Performance and Capacity of Household Refrigerators, Refrigerator-Freezers, and Freezers	CSA	C300-00 (R2005)

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Subject	Title	Publisher	Reference
	Energy Performance Standard for Food Service Refrigerators and Freezers	CSA	C827-98 (R2003)
	Refrigeration Equipment	CSA	CAN/CSA-C22.2 No. 120-M91 (R2004)
Commercial	Dispensing Freezers	NSF	NSF/ANSI 6-2005
	Commercial Refrigerators and Freezers	NSF	NSF/ANSI 7-2001
	Commercial Refrigerators and Freezers (1995)	UL	ANSI/UL 471
	Ice Makers (1995)	UL	ANSI/UL 563
	Ice Cream Makers (2005)	UL	ANSI/UL 621
Household	Household Refrigerators, Refrigerator-Freezers and Freezers	AHAM	ANSI/AHAM HRF-1-2004
	Household Refrigerators and Freezers (1993)	UL/CSA	ANSI/UL 250/C22.2 No. 63-93 (R1999)
Fuels	Threshold Limit Values for Chemical Substances (updated annually)	ACGIH	ACGIH
	International Gas Fuel Code (2006)	AGA/NFPA	ANSI Z223.1/NPFA 54-2006
	Reporting of Fuel Properties when Testing Diesel Engines with Alternative Fuels Derived from Biological Materials	ASABE	ASAE EP552-2001
	Coal Pulverizers	ASME	PTC 4.2 1969 (RA03)
	Classification of Coals by Rank	ASTM	ASTM D388-05
	Specification for Fuel Oils	ASTM	ASTM D396-05
	Test Method for Determination of Homogeneity and Miscibility in Automotive Engine Oils	ASTM	ASTM D922-00a
	Specification for Diesel Fuel Oils	ASTM	ASTM D975-05
	Specification for Gas Turbine Fuel Oils	ASTM	ASTM D2880-03
	Specification for Kerosene	ASTM	ASTM D3699-05
	Practice for Receipt, Storage and Handling of Fuels	ASTM	ASTM D4418-00
	Test Method for Determination of Yield Stress and Apparent Viscosity of Used Engine Oils at Low Temperature	ASTM	ASTM D6896-03 E01
	Test Method for Total Sulfur in Naphthas, Distillates, Reformulated Gasolines, Diesels, Biodiesels, and Motor Fuels by Oxidative Combustion and Electrochemical Detection	ASTM	ASTM D6920-03
	Test Method for Measurement of Hindered Phenolic and Aromatic Amine Antioxidant Content in Non-Zinc Turbine Oils by Linear Sweep Voltammetry	ASTM	ASTM D6971-04
	Practice for Enumeration of Viable Bacteria and Fungi in Liquid Fuels—Filtration and Culture Procedures	ASTM	ASTM D6974-04a
	Test Method for Evaluation of Aeration Resistance of Engine Oils in Direct-Injected Turbocharged Automotive Diesel Engine	ASTM	ASTM D6984-05a
	Specification for Middle Distillate Fuel Oil-Military Marine Applications	ASTM	ASTM D6985-04a
	Test Method for Determination of Ignition Delay and Derived Cetane Number DCN of Diesel Fuel Oils by Combustion in a Constant Volume Chamber	ASTM	ASTM D6890-04
	Test Method for Determination of Total Sulfur in Light Hydrocarbon, Motor Fuels, and Oils by Online Gas Chromatography with Flame Photometric Detection	ASTM	ASTM D7041-04
	Test Method for Sulfur in Gasoline and Diesel Fuel by Monochromatic Wavelength Dispersive X-Ray Fluorescence Spectrometry	ASTM	ASTM D7044-04a
	New Draft Standard Test Method for Flash Point by Modified Continuously Closed Cup Flash Point Tester	ASTM	ASTM D7094-04
	Test Method for Determining the Viscosity-Temperature Relationship of Used and Soot-Containing Engine Oils at Low Temperatures	ASTM	ASTM D7110-05a
	Test Method for Determination of Trace Elements in Middle Distillate Fuels by Inductively Coupled Plasma Atomic Emission Spectrometry (ICPAES)	ASTM	ASTM D7111-05
	Test Method for Determining Stability and Compatibility of Heavy Fuel Oils and Crude Oils by Heavy Fuel Oil Stability Analyzer (Optical Detection)	ASTM	ASTM D7112-05a
	Test Method for Determination of Intrinsic Stability of Asphaltene-Containing Residues, Heavy Fuel Oils, and Crude Oils	ASTM	ASTM D7157-05
	Test Method for Hydrogen Content of Middle Distillate Petroleum Products by Low-Resolution Pulsed Nuclear Magnetic Resonance Spectroscopy	ASTM	ASTM D7171-05
	Gas-Fired Central Furnaces	CSA	ANSI Z21.47-2003/CSA 2.3-2003
	Gas Unit Heaters and Gas-Fired Duct Furnaces	CSA	ANSI Z83.8-2002/CSA-2.6-2002 (R2005)
	Industrial and Commercial Gas-Fired Package Furnaces	CSA	CGA 3.2-1976 (R2003)
	Uniform Mechanical Code (2006)	IAPMO	Chapter 13
	Uniform Plumbing Code (2006)	IAPMO	Chapter 12
	International Fuel Gas Code (2006)	ICC	IFGC
	Standard Gas Code (1999)	SBCCI	SGC
	Commercial-Industrial Gas Heating Equipment (1999)	UL	UL 795
Furnaces	Commercial Applications, Systems, and Equipment, 1st ed.	ACCA	ACCA Manual CS
	Residential Equipment Selection, 2nd ed.	ACCA	ANSI/ACCA Manual S
	Method of Testing for Annual Fuel Utilization Efficiency of Residential Central Furnaces and Boilers	ASHRAE	ANSI/ASHRAE 103-1993
	Prevention of Furnace Explosions/Implosions in Multiple Burner Boilers	NFPA	NFPA 8502-99

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Subject	Title	Publisher	Reference
	Standard Mechanical Code (1997)	SBCCI	SMC
	Residential Gas Detectors (2000)	UL	ANSI/UL 1484
	Heating and Cooling Equipment (2005)	UL/CSA	ANSI/UL 1995/C22.2 No. 236-95
	Single and Multiple Station Carbon Monoxide Alarms (1996)	UL	ANSI/UL 2034
Gas	International Gas Fuel Code (2006)	AGA/NFPA	ANSI Z223.1/NFPA 54-2006
	Gas-Fired Central Furnaces	CSA	ANSI Z21.47-2003/CSA 2.3-2003
	Gas Unit Heaters and Gas-Fired Duct Furnaces	CSA	ANSI Z83.8-2002/CSA-2.6-2002
	Industrial and Commercial Gas-Fired Package Furnaces	CSA	CGA 3.2-1976 (R2003)
	International Fuel Gas Code (2006)	ICC	IFGC
	Standard Gas Code (1999)	SBCCI	SGC
	Commercial-Industrial Gas Heating Equipment (1999)	UL	UL 795
Oil	Specification for Fuel Oils	ASTM	ASTM D396-04a
	Specification for Diesel Fuel Oils	ASTM	ASTM D975-04b E01
	Test Method for Smoke Density in Flue Gases from Burning Distillate Fuels	ASTM	ASTM D2156-94 (2003)
	Standard Test Method for Vapor Pressure of Liquefied Petroleum Gases (LPG) (Expansion Method)	ASTM	ASTM D6897-2003a
	Oil Burning Stoves and Water Heaters	CSA	B140.3-1962 (R2001)
	Oil-Fired Warm Air Furnaces	CSA	B140.4-04
	Installation of Oil-Burning Equipment	NFPA	NFPA 31-06
	Oil-Fired Central Furnaces (1994)	UL	UL 727
	Oil-Fired Floor Furnaces (2003)	UL	ANSI/UL 729
	Oil-Fired Wall Furnaces (2003)	UL	ANSI/UL 730
Solid Fuel	Installation Code for Solid-Fuel-Burning Appliances and Equipment	CSA	B365-01
	Solid-Fuel-Fired Central Heating Appliances	CSA	CAN/CSA-B366.1-M91 (R2002)
	Solid-Fuel and Combination-Fuel Central and Supplementary Furnaces (1995)	UL	ANSI/UL 391
Heaters	Gas-Fired High-Intensity Infrared Heaters	CSA	ANSI Z83.19-2001/CSA 2.35-2001 (R2005)
	Gas-Fired Low-Intensity Infrared Heaters	CSA	ANSI Z83.20-2001/CSA 2.34-2001 (R2005)
	Threshold Limit Values for Chemical Substances (updated annually)	ACGIH	ACGIH
	Industrial Ventilation: A Manual of Recommended Practice, 25th ed. (2004)	ACGIH	ACGIH
	Thermal Performance Testing of Solar Ambient Air Heaters	ASABE	ANSI/ASAE S423-2001
	Air Heaters	ASME	ASME PTC 4.3-1968 (RA91)
	Guide for Construction of Solid Fuel Burning Masonry Heaters	ASTM	ASTM E1602-03
	Non-Recirculating Direct Gas-Fired Industrial Air Heaters	CSA	ANSI Z83.4-2003/CSA 3.7-2003
	Electric Duct Heaters	CSA	C22.2 No. 155-M1986 (R2004)
	Portable Kerosene-Fired Heaters	CSA	CAN3-B140.9.3 M86 (R2001)
	Standards for Closed Feedwater Heaters, 7th ed.	HEI	HEI 2004
	Electric Heating Appliances (2005)	UL	ANSI/UL 499
	Electric Oil Heaters (2003)	UL	ANSI/UL 574
	Oil-Fired Air Heaters and Direct-Fired Heaters (1993)	UL	UL 733
	Electric Dry Bath Heaters (2004)	UL	ANSI/UL 875
	Oil-Burning Stoves (1993)	UL	ANSI/UL 896
Engine	Electric Engine Preheaters and Battery Warmers for Diesel Engines	SAE	SAE J1310-1993
	Selection and Application Guidelines for Diesel, Gasoline, and Propane Fired Liquid Cooled Engine Pre-Heaters	SAE	SAE J1350-1988
	Fuel Warmer—Diesel Engines	SAE	SAE J1422-1996
Nonresidential	Installation of Electric Infrared Brooding Equipment	ASABE	ASAE EP258.3-2004
	Gas-Fired Construction Heaters	CSA	ANSI Z83.7-2000/CSA 2.14-2000
	Recirculating Direct Gas-Fired Industrial Air Heaters	CSA	ANSI Z83.18-2004
	Portable Industrial Oil-Fired Heaters	CSA	B140.8-1967 (R2001)
	Fuel-Fired Heaters—Air Heating—for Construction and Industrial Machinery	SAE	SAE J1024-1989
	Commercial-Industrial Gas Heating Equipment (1999)	UL	UL 795
	Electric Heaters for Use in Hazardous (Classified) Locations (1995)	UL	ANSI/UL 823
Pool	Methods of Testing and Rating Pool Heaters	ASHRAE	ANSI/ASHRAE 146-2006
	Gas-Fired Pool Heaters	CSA	ANSI Z21.56A-2001/CSA 4.7-2001
	Oil-Fired Service Water Heaters and Swimming Pool Heaters	CSA	B140.12-03
Room	Specification for Room Heaters, Pellet Fuel Burning Type	ASTM	ASTM E1509-04
	Gas-Fired Room Heaters, Vol. II, Unvented Room Heaters	CSA	ANSI Z21.11.2-2002
	Gas-Fired Unvented Catalytic Room Heaters for Use with Liquefied Petroleum (LP) Gases	CSA	ANSI Z21.76-1994 (R2000)
	Vented Gas-Fired Space Heating Appliances	CSA	ANSI Z21.86-2004/CSA 2.32-2004
	Vented Gas Fireplace Heaters	CSA	ANSI Z21.88-2005/CSA 2.33-2005
	Unvented Kerosene-Fired Room Heaters and Portable Heaters (1993)	UL	UL 647
	Movable and Wall- or Ceiling-Hung Electric Room Heaters (2000)	UL	UL 1278

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Subject	Title	Publisher	Reference
	Fixed and Location-Dedicated Electric Room Heaters (1997)	UL	UL 2021
	Solid Fuel-Type Room Heaters (1996)	UL	ANSI/UL 1482
Transport	Heater, Airplane, Engine Exhaust Gas to Air Heat Exchanger Type	SAE	SAE ARP86A-1996
	Installation, Heaters, Airplane, Internal Combustion Heater Exchange Type	SAE	SAE ARP266-1996
	Heater, Aircraft, Internal Combustion Heat Exchanger Type	SAE	SAE AS8040A-1996
	Motor Vehicle Heater Test Procedure	SAE	SAE J638-1998
	Heater, Aircraft, Internal Combustion Heat Exchanger Type	SAE	SAE AS8040A-1996
Unit	Gas Unit Heaters and Gas-Fired Duct Furnaces	CSA	ANSI Z83.8-2002/CSA-2.6-2002 (R2005)
	Oil-Fired Unit Heaters (1995)	UL	ANSI/UL 731
Heat Exchangers	Remote Mechanical-Draft Evaporative Refrigerant Condensers	ARI	ARI 490-2003
	Method of Testing Air-to-Air Heat Exchangers	ASHRAE	ANSI/ASHRAE 84-1991
	Boiler and Pressure Vessel Code—Section VIII, Division 1: Pressure Vessels	ASME	ASME BPVC-2004
	Single Phase Heat Exchangers	ASME	ASME PTC 12.5-2000 (RA05)
	Air Cooled Heat Exchangers	ASME	ASME PTC 30-1991 (RA05)
	Standard Methods of Test for Rating the Performance of Heat-Recovery Ventilators	CSA	C439-00 (R2005)
	Standards for Power Plant Heat Exchangers, 4th ed.	HEI	HEI 2004
	Standards of Tubular Exchanger Manufacturers Association, 8th ed. (1999)	TEMA	TEMA
	Refrigerant-Containing Components and Accessories, Nonelectrical (2001)	UL	ANSI/UL 207
Heating	Commercial Applications, Systems, and Equipment, 1st ed.	ACCA	ACCA Manual CS
	Comfort, Air Quality, and Efficiency by Design	ACCA	ACCA Manual RS
	Residential Equipment Selection, 2nd ed.	ACCA	ANSI/ACCA Manual S
	Heating, Ventilating and Cooling Greenhouses	ASABE	ANSI/ASAE EP406.4-2003
	Automatic Flue-Pipe Dampers for Use with Oil-Fired Appliances	CSA	B140.14-M1979 (R2001)
	Heater Elements	CSA	C22.2 No.72-M1984 (R2004)
	Determining the Required Capacity of Residential Space Heating and Cooling Appliances	CSA	CAN/CSA-F280-M90 (R2004)
	Heat Loss Calculation Guide (2001)	HYDI	HYDI H-22
	Residential Hydronic Heating Installation/Design	HYDI	IBR Guide
	Radiant Floor Heating (1995)	HYDI	HYDI 004
	Advanced Installation Guide (Commercial) for Hot Water Heating Systems (2001)	HYDI	HYDI 250
	Environmental Systems Technology, 2nd ed. (1999)	NEBB	NEBB
	Pulverized Fuel Systems	NFPA	NFPA 8503-97
	Aircraft Electrical Heating Systems	SAE	SAE AIR860A-2000
	Heating Value of Fuels	SAE	SAE J1498-2005
	Performance Test for Air-Conditioned, Heated, and Ventilated Off-Road Self-Propelled Work Machines	SAE	SAE J1503-2004
	HVAC Systems Applications, 1st ed.	SMACNA	SMACNA 1987
	Electric Baseboard Heating Equipment (1994)	UL	ANSI/UL 1042
	Electric Duct Heaters (2004)	UL	ANSI/UL 1996
	Heating and Cooling Equipment (2005)	UL/CSA	ANSI/UL 1995/C22.2 No. 236-95
Heat Pumps	Commercial Applications, Systems, and Equipment, 1st ed.	ACCA	ACCA Manual CS
	Geothermal Heat Pump Training Certification Program	ACCA	ACCA Training Manual
	Heat Pumps Systems, Principles and Applications, 2nd ed.	ACCA	ACCA Manual H
	Residential Equipment Selection, 2nd ed.	ACCA	ANSI/ACCA Manual S
	Industrial Ventilation: A Manual of Recommended Practice, 25th ed. (2004)	ACGIH	ACGIH
	Commercial and Industrial Unitary Air-Conditioning and Heat Pump Equipment	ARI	ARI 340/360-2004
	Ground Source Closed-Loop Heat Pumps	ARI	ARI 330-98
	Ground Water-Source Heat Pumps	ARI	ARI 325-98
	Water-Source Heat Pumps	ARI	ARI 320-98
	Methods of Testing for Rating Electrically Driven Unitary Air-Conditioning and Heat Pump Equipment	ASHRAE	ANSI/ASHRAE 37-2005
	Methods of Testing for Rating Seasonal Efficiency of Unitary Air-Conditioners and Heat Pumps	ASHRAE	ANSI/ASHRAE 116- (RA05)
	Performance Standard for Split-System Central Air-Conditioners and Heat Pumps	CSA	CAN/CSA-C273.3-M94 (R2005)
	Installation Requirements for Air-to-Air Heat Pumps	CSA	C273.5-1980 (R2005)
	Performance of Direct-Expansion (DX) Ground-Source Heat Pumps	CSA	C748-94 (R1999)
	Water-Source Heat Pumps—Testing and Rating for Performance, Part 1: Water-to-Air and Brine-to-Air Heat Pumps	CSA	CAN/CSA C13256-1-01
	Part 2: Water-to-Water and Brine-to-Water Heat Pumps	CSA	CAN/CSA C13256-2-01 (R2005)
	Heating and Cooling Equipment (2005)	UL/CSA	ANSI/UL 1995/C22.2 No. 236-95
Gas-Fired	Gas-Fired, Heat Activated Air Conditioning and Heat Pump Appliances	CSA	ANSI Z21.40.1-1996 (R2002)/CGA 2.91-M96

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Subject	Title	Publisher	Reference
	Gas-Fired, Work Activated Air Conditioning and Heat Pump Appliances (Internal Combustion)	CSA	ANSI Z21.40.2-1996 (R2002)/CGA 2.92-M96
	Performance Testing and Rating of Gas-Fired Air Conditioning and Heat Pump Appliances	CSA	ANSI Z21.40.4-1996 (R2002)/CGA 2.94-M96
Heat Recovery	Gas Turbine Heat Recovery Steam Generators	ASME	ANSI/ASME PTC 4.4-1981 (RA03)
	Water Heaters, Hot Water Supply Boilers, and Heat Recovery Equipment	NSF	NSF/ANSI 5-2005
Humidifiers	Commercial Applications, Systems, and Equipment, 1st ed.	ACCA	ACCA Manual CS
	Comfort, Air Quality, and Efficiency by Design	ACCA	ACCA Manual RS
	Bioaerosols: Assessment and Control (1999)	ACGIH	ACGIH
	Humidifiers	AHAM	ANSI/AHAM HU-1-2003
	Central System Humidifiers for Residential Applications	ARI	ARI 610-2004
	Self-Contained Humidifiers for Residential Applications	ARI	ARI 620-2004
	Commercial and Industrial Humidifiers	ARI	ANSI/ARI 640-2005
	Humidifiers (2001)	UL/CSA	ANSI/UL 998/C22.2 No. 104-93
Ice Makers	Performance Rating of Automatic Commercial Ice Makers	ARI	ARI 810-2003
	Ice Storage Bins	ARI	ARI 820-2000
	Methods of Testing Automatic Ice Makers	ASHRAE	ANSI/ASHRAE 29-1988 (RA05)
	Refrigeration Equipment	CSA	CAN/CSA-C22.2 No. 120-M91 (R2004)
	Performance of Automatic Ice-Makers and Ice Storage Bins	CSA	C742-98 (R2003)
	Automatic Ice Making Equipment	NSF	NSF/ANSI 12-2005
	Ice Makers (1995)	UL	ANSI/UL 563
Incinerators	Large Incinerators	ASME	ASME PTC 33-1978 (RA91)
	Incinerators and Waste and Linen Handling Systems and Equipment	NFPA	NFPA 82-04
	Residential Incinerators (1993)	UL	UL 791
Indoor Air Quality	Good HVAC Practices for Residential and Commercial Buildings (2003)	ACCA	ACCA
	Comfort, Air Quality, and Efficiency by Design (Residential) (1997)	ACCA	ACCA Manual RS
	Bioaerosols: Assessment and Control (1999)	ACGIH	ACGIH
	Ventilation for Acceptable Indoor Air Quality	ASHRAE	ANSI/ASHRAE 62.1-2004
	Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings	ASHRAE	ANSI/ASHRAE 62.2-2004
	Test Method for Determination of Volatile Organic Chemicals in Atmospheres (Canister Sampling Methodology)	ASTM	ASTM D5466-01
	Guide for Using Probability Sampling Methods in Studies of Indoor Air Quality in Buildings	ASTM	ASTM D5791-95 (2001)
	Guide for Using Indoor Carbon Dioxide Concentrations to Evaluate Indoor Air Quality and Ventilation	ASTM	ASTM D6245-98 (2002)
	Guide for Placement and Use of Diffusion Controlled Passive Monitors for Gaseous Pollutants in Indoor Air	ASTM	ASTM D6306-98 (2003)
	Test Method for Determination of Metals and Metalloids Airborne Particulate Matter by Inductively Coupled Plasma Atomic Emissions Spectrometry (ICP-AES)	ASTM	ASTM D7035-04
	Test Method for Metal Removal Fluid Aerosol in Workplace Atmospheres	ASTM	ASTM D7049-04
	Practice for Emission Cells for the Determination of Volatile Organic Emissions from Materials/Products	ASTM	ASTM D7143-05
	Practice for Collection of Surface Dust by Micro-Vacuum Sampling for Subsequent Metals Determination	ASTM	ASTM D7144-05a
	Test Method for Determination of Beryllium in the Workplace Using Field-Based Extraction and Fluorescence Detection	ASTM	ASTM D7202-05
	Practice for Referencing Suprathreshold Odor Intensity	ASTM	ASTM E544-99 (2004)
	Guide for Specifying and Evaluating Performance of a Single Family Attached and Detached Dwelling—Indoor Air Quality	ASTM	ASTM E2267-04
	Classification for Serviceability of an Office Facility for Thermal Environment and Indoor Air Conditions	ASTM	ASTM E2320-04
	Practice for Continuous Sizing and Counting of Airborne Particles in Dust-Controlled Areas and Clean Rooms Using Instruments Capable of Detecting Single Sub-Micrometre and Larger Particles	ASTM	ASTM F50-92(2001)E01
	Ambient Air—Determination of Mass Concentration of Nitrogen Dioxide—Modified Griess-Saltzman Method	ISO	ISO 6768:1998
	Air Quality—Exchange of Data	ISO	ISO 7168:1999
	Environmental Tobacco Smoke—Estimation of Its Contribution to Respirable Suspended Particles—Determination of Particulate Matter by Ultraviolet Absorptance and by Fluorescence	ISO	ISO 15593:2001
	Indoor Air—Part 3: Determination of Formaldehyde and Other Carbonyl Compounds—Active Sampling Method	ISO	ISO 16000-3:2001
	Workplace Air Quality—Sampling and Analysis of Volatile Organic Compounds by Solvent Desorption/Gas Chromatography—Part 1: Pumped Sampling Method	ISO	ISO 16200-1:2001
	Part 2: Diffusive Sampling Method	ISO	ISO 16200-2:2000

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Subject	Title	Publisher	Reference
	Workplace Air Quality—Determination of Total Isocyanate Group in Air Using 2-(1-Methoxyphenyl) Piperazine and Liquid Chromatography	ISO	ISO 16702-1:2001
	Installation of Household Carbon Monoxide (CO) Warning Equipment	NFPA	NFPA 720-2005
	Indoor Air Quality—A Systems Approach, 3rd ed.	SMACNA	SMACNA 1998
	IAQ Guidelines for Occupied Buildings Under Construction, 1st ed.	SMACNA	SMACNA 1995
	Single and Multiple Station Carbon Monoxide Alarms	UL	ANSI/UL 2034
Aircraft	Guide for Selecting Instruments and Methods for Measuring Air Quality in Aircraft Cabins	ASTM	ASTM D6399-04
	Guide for Deriving Acceptable Levels of Airborne Chemical Contaminants in Aircraft Cabins Based on Health and Comfort Considerations	ASTM	ASTM D7034-04
Insulation	Guidelines for Use of Thermal Insulation in Agricultural Buildings	ASABE	ANSI/ASAE S401.2-2003
	Terminology Relating to Thermal Insulating Materials	ASTM	ASTM C168-05a
	Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus	ASTM	ASTM C177-04
	Test Method for Steady-State Heat Transfer Properties of Horizontal Pipe Insulations	ASTM	ASTM C335-05a
	Practice for Prefabrication and Field Fabrication of Thermal Insulating Fitting Covers for NPS Piping, Vessel Lagging, and Dished Head Segments	ASTM	ASTM C450-02
	Test Method for Steady-State and Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus	ASTM	ASTM C518-04
	Specification for Preformed Flexible Elastometric Cellular Thermal Insulation in Sheet and Tubular Form	ASTM	ASTM C534-05
	Specification for Cellular Glass Thermal Insulation	ASTM	ASTM C552-03
	Specification for Rigid, Cellular Polystyrene Thermal Insulation	ASTM	ASTM C578-05a
	Practice for Inner and Outer Diameters of Rigid Thermal Insulation for Nominal Sizes of Pipe and Tubing (NPS System)	ASTM	ASTM C585-90 (2004)
	Specification for Unfaced Preformed Rigid Cellular Polyisocyanurate Thermal Insulation	ASTM	ASTM C591-05
	Practice for Determination of Heat Gain or Loss and the Surface Temperature of Insulated Pipe and Equipment Systems by the Use of a Computer Program	ASTM	ASTM C680-04e02
	Specification for Adhesives for Duct Thermal Insulation	ASTM	ASTM C916-8(2001)e1
	Classification of Potential Health and Safety Concerns Associated with Thermal Insulation Materials and Accessories	ASTM	ASTM C930-05
	Practice for Thermographic Inspection of Insulation Installations in Envelope Cavities of Frame Buildings	ASTM	ASTM C1060-90 (2003)
	Specification for Fibrous Glass Duct Lining Insulation (Thermal and Sound Absorbing Material)	ASTM	ASTM C1071-05
	Specification for Faced or Unfaced Rigid Cellular Phenolic Thermal Insulation	ASTM	ASTM C1126-04
	Practice for Installation and Use of Radiant Barrier Systems (RBS) in Building Construction	ASTM	ASTM C1158-05
	Test Method for Steady-State and Thermal Performance of Building Assemblies by Means of a Hot Box Apparatus	ASTM	ASTM C1363-05
	Specification for Perpendicularly Oriented Mineral Fiber Roll and Sheet Thermal Insulation for Pipes and Tanks	ASTM	ASTM C1393-00a
	Guide for Measuring and Estimating Quantities of Insulated Piping and Components	ASTM	ASTM C1409-98 (2003)
	Specification for Cellular Melamine Thermal and Sound Absorbing Insulation	ASTM	ASTM C1410-05a
	Guide for Selecting Jacketing Materials for Thermal Insulation	ASTM	ASTM C1423-98 (2003)
	Specification for Preformed Flexible Cellular Polyolefin Thermal Insulation in Sheet and Tubular Form	ASTM	ASTM C1427-04
	Specification for Polyimide Flexible Cellular Thermal and Sound Absorbing Insulation	ASTM	ASTM C1482-04
	Specification for Cellulosic Fiber Stabilized Thermal Insulation	ASTM	ASTM C1497-04
	Test Method for Characterizing the Effect of Exposure to Environmental Cycling on Thermal Performance of Insulation Products	ASTM	ASTM C1512-01
	Specification for Flexible Polymeric Foam Sheet Insulation Used as a Thermal and Sound Absorbing Liner for Duct Systems	ASTM	ASTM C1534-04
	Standard Guide for Development of Standard Data Records for Computerization of Thermal Transmission Test Data for Thermal Insulation	ASTM	ASTM C1558-03
	Guide for Determining Blown Density of Pneumatically Applied Loose Fill Mineral Fiber Thermal Insulation	ASTM	ASTM C1574-04
	Test Method for Determining the Moisture Content of Inorganic Insulation Materials by Weight	ASTM	ASTM C1616-05
	Specification for Cellular Polypropylene Thermal Insulation	ASTM	ASTM C1631-05
	Classification for Rating Sound Insulation	ASTM	ASTM E413-04
	Test Method for Determining the Drainage Efficiency of Exterior Insulation and Finish Systems (EIFS) Clad Wall Assemblies	ASTM	ASTM E2273-03
	Practice for Use of Test Methods E96 for Determining the Water Vapor Transmission (WVT) of Exterior Insulation and Finish Systems	ASTM	ASTM E2321-03
	Thermal Insulation—Materials, Products, and Systems—Vocabulary	ISO	ISO 9229:1991
	National Commercial and Industrial Insulation Standards, 5th ed.	MICA	MICA 1999

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Subject	Title	Publisher	Reference
	Accepted Industry Practices for Sheet Metal Lagging, 1st ed.	SMACNA	SMACNA 2002
Louvers	Laboratory Methods of Testing Dampers for Rating	AMCA	AMCA 500-D-98
	Laboratory Methods of Testing Louvers for Rating	AMCA	AMCA 500-L-99
Lubricants	Methods of Testing the Floc Point of Refrigeration Grade Oils	ASHRAE	ANSI/ASHRAE 86-1994 (RA06)
	Test Method for Pour Point of Petroleum Products	ASTM	ASTM D97-05a
	Classification of Industrial Fluid Lubricants by Viscosity System	ASTM	ASTM D2422-97 (2002)
	Test Method for Relative Molecular Weight (Relative Molecular Mass) of Hydrocarbons by Thermoelectric Measurement of Vapor Pressure	ASTM	ASTM D2503-92 (2002) E01
	Test Method for Determination of Moderately High Temperature Piston Deposits by Thermo-Oxidation Engine Oil Simulation Test	ASTM	ASTM D7097-05
	Petroleum Products—Corrosiveness to Copper—Copper Strip Test	ISO	ISO 2160:1998
Measurement	Industrial Ventilation: A Manual of Recommended Practice, 25th ed. (2004)	ACGIH	ACGIH
	Engineering Analysis of Experimental Data	ASHRAE	ASHRAE *Guideline* 2-2005
	Standard Method for Measurement of Proportion of Lubricant in Liquid Refrigerant	ASHRAE	ANSI/ASHRAE 41.4-1996 (RA06)
	Standard Method for Measurement of Moist Air Properties	ASHRAE	ANSI/ASHRAE 41.6-1994 (RA06)
	Method of Measuring Solar-Optical Properties of Materials	ASHRAE	ANSI/ASHRAE 74-1988
	Standard Methods of Measuring and Expressing Building Energy Performance	ASHRAE	ANSI/ASHRAE 105-1984 (RA99)
	Method for Establishing Installation Effects on Flowmeters	ASME	ASME MFC-10M-2000
	Test Uncertainty	ASME	ASME PTC 19.1-1998 (RA04)
	Measurement of Industrial Sound	ASME	ANSI/ASME PTC 36-2004
	Test Methods for Water Vapor Transmission of Materials	ASTM	ASTM E96-05
	Specification for Temperature-Electromotive Force (EMF) Tables for Standardized Thermocouples	ASTM	ASTM E230-03
	Practice for Continuous Sizing and Counting of Airborne Particles in Dust-Controlled Areas and Clean Rooms Using Instruments Capable of Detecting Single Sub-Micrometre and Larger Particles	ASTM	ASTM F50-92(2001)E01
	Use of the International System of Units (SI): The Modern Metric System	IEEE/ASTM	IEEE/ASTM-SI10-2002
	Ergonomics of the Thermal Environment—Instruments for Measuring Physical Quantities	ISO	ISO 7726:1998
	Ergonomics of the Thermal Environment—Determination of Metabolic Rate	ISO	ISO 8996:2004
	Ergonomics of the Thermal Environment—Estimation of the Thermal Insulation and Evaporative Resistance of a Clothing Ensemble	ISO	ISO 9920:1995
Fluid Flow	Standard Methods of Measurement of Flow of Liquids in Pipes Using Orifice Flowmeters	ASHRAE	ANSI/ASHRAE 41.8-1989
	Calorimeter Test Methods for Mass Flow Measurements of Volatile Refrigerants	ASHRAE	ANSI/ASHRAE 41.9-2000 (RA06)
	Flow Measurement	ASME	ASME PTC 19.5-2004
	Glossary of Terms Used in the Measurement of Fluid Flow in Pipes	ASME	ASME MFC-1M-2003
	Measurement Uncertainty for Fluid Flow in Closed Conduits	ASME	ANSI/ASME MFC-2M-1983 (RA01)
	Measurement of Fluid Flow in Pipes Using Orifice, Nozzle, and Venturi	ASME	ASME MFC-3M-2004
	Measurement of Liquid Flow in Closed Conduits Using Transit-Time Ultrasonic Flowmeters	ASME	ASME MFC-5M-1985 (RA01)
	Measurement of Fluid Flow in Pipes Using Vortex Flowmeters	ASME	ASME MFC-6M-1998 (RA05)
	Fluid Flow in Closed Conduits: Connections for Pressure Signal Transmissions Between Primary and Secondary Devices	ASME	ASME MFC-8M-2001
	Measurement of Liquid Flow in Closed Conduits by Weighing Method	ASME	ASME MFC-9M-1988 (RA01)
	Measurement of Fluid Flow by Means of Coriolis Mass Flowmeters	ASME	ASME MFC-11M-2003
	Measurement of Fluid Flow Using Small Bore Precision Orifice Meters	ASME	ASME MFC-14M-2003
	Measurement of Fluid Flow in Closed Conduits by Means of Electromagnetic Flowmeters	ASME	ASME MFC-16M-1995 (R01)
	Measurement of Fluid Flow Using Variable Area Meters	ASME	ASME MFC-18M-2001
	Test Method for Determining the Moisture Content of Inorganic Insulation Materials by Weight	ASTM	ASTM C1616-05
	Test Method for Indicating Wear Characteristics of Petroleum Hydraulic Fluids in a High Pressure Constant Volume Vane Pump	ASTM	ASTM D6973-05
	Test Method for Dynamic Viscosity and Density of Liquids by Stabinger Viscometer and the Calculation of Kinematic Viscosity	ASTM	ASTM D7042-04
	Test Method for Indicating Wear Characteristics of Petroleum and Non-Petroleum Hydraulic Fluids in a Constant Volume Vane Pump	ASTM	ASTM D7043-04a
	Practice for Calculating Viscosity of a Blend of Petroleum Products	ASTM	ASTM D7152-05
	Test Method for Same-Different Test	ASTM	ASTM E2139-05
	Practice for Field Use of Pyranometers, Pyrheliometers, and UV Radiometers	ASTM	ASTM G183-05
Gas Flow	Standard Methods for Laboratory Airflow Measurement	ASHRAE	ANSI/ASHRAE 41.2-1987 (RA92)
	Method of Test for Measurement of Flow of Gas	ASHRAE	ANSI/ASHRAE 41.7-1984 (RA06)
	Measurement of Gas Flow by Means of Critical Flow Venturi Nozzles	ASME	ANSI/ASME MFC-7M-1987 (RA01)
	Measurement of Gas Flow by Turbine Meters	ASME	ANSI/ASME MFC-4M-1986 (RA03)
Pressure	Standard Method for Pressure Measurement	ASHRAE	ANSI/ASHRAE 41.3-1989

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Subject	Title	Publisher	Reference
	Pressure Gauges and Gauge Attachments	ASME	ASME B40.100-1998
	Pressure Measurement	ASME	ANSI/ASME PTC 19.2-1987 (RA04)
Temperature	Standard Method for Temperature Measurement	ASHRAE	ANSI/ASHRAE 41.1-1986 (RA06)
	Thermometers, Direct Reading and Remote Reading	ASME	ASME B40.200-2001
	Temperature Measurement	ASME	ASME PTC 19.3-1974 (RA04)
	Total Temperature Measuring Instruments (Turbine Powered Subsonic Aircraft)	SAE	SAE AS793A-2001
Thermal	Method of Testing Thermal Energy Meters for Liquid Streams in HVAC Systems	ASHRAE	ANSI/ASHRAE 125-1992 (RA06)
	Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus	ASTM	ASTM C177-04
	Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus	ASTM	ASTM C518-04
	Test Method for Thermal Performance of Building Assemblies by Means of a Calibrated Hot Box	ASTM	ASTM C976-90(1996)e1
	Practice for In-Situ Measurement of Heat Flux and Temperature on Building Envelope Components	ASTM	ASTM C1046-95(2001)
	Practice for Determining Thermal Resistance of Building Envelope Components from In-Situ Data	ASTM	ASTM C1155-95(2001)
Mobile Homes and Recreational Vehicles	Residential Load Calculation, 8th ed.	ACCA	ANSI/ACCA Manual J
	Recreational Vehicle Cooking Gas Appliances	CSA	ANSI Z21.57-2005
	Oil-Fired Warm Air Heating Appliances for Mobile Housing and Recreational Vehicles	CSA	B140.10-1974 (R2001)
	Mobile Homes	CSA	CAN/CSA-Z240 MH Series-92 (R2005)
	Recreational Vehicles	CSA	CAN/CSA-Z240 RV Series-99 (R2004)
	Gas Supply Connectors for Manufactured Homes	IAPMO	IAPMO TS 9-2003
	Fuel Supply: Manufactured/Mobile Home Parks & Recreational Vehicle Parks	IAPMO	Chapter 13, Part II
	Manufactured Housing Construction and Safety Standards	ICC/ANSI	ICC/ANSI 2.0-1998
	Manufactured Housing	NFPA	NFPA 501-05
	Recreational Vehicles	NFPA	NFPA 1192-05
	Plumbing System Components for Manufactured Homes and Recreational Vehicles	NSF	NSF/ANSI 24-1988
	Low Voltage Lighting Fixtures for Use in Recreational Vehicles (2005)	UL	ANSI/UL 234
	Liquid Fuel-Burning Heating Appliances for Manufactured Homes and Recreational Vehicles (1995)	UL	ANSI/UL 307A
	Gas-Burning Heating Appliances for Manufactured Homes and Recreational Vehicles (1995)	UL	UL 307B
	Gas-Fired Cooking Appliances for Recreational Vehicles (1993)	UL	UL 1075
Motors and Generators	Installation and Maintenance of Farm Standby Electric Power	ASABE	ANSI/ASAE EP364.2-2003
	Testing of Nuclear Air Treatment Systems	ASME	ASME N510-1989 (RA95)
	Nuclear Power Plant Air-Cleaning Units and Components	ASME	ASME N509-2002
	Fired Steam Generators	ASME	ASME PTC 4-1998
	Gas Turbine Heat Recovery Steam Generators	ASME	ASME PTC 4.4-1981 (RA03)
	Test Methods for Film-Insulated Magnet Wire	ASTM	ASTM D1676-03
	Test Method for Evaluation of Engine Oils in a High Speed, Single-Cylinder Diesel Engine—Caterpillar 1R Test Procedure	ASTM	ASTM D6923-05
	Test Method for Evaluation of Diesel Engine Oils in the T-11 Exhaust Gas Recirculation Diesel Engine	ASTM	ASTM D7156-05
	Energy Efficiency Test Methods for Three-Phase Induction Motors	CSA	C390-98 (R2005)
	Motors and Generators	CSA	C22.2 No. 100-04
	Emergency Electrical Power Supply for Buildings	CSA	CSA C282-05
	Energy Efficiency Test Methods for Single- and Three-Phase Small Motors	CSA	CAN/CSA C747-94 (R2005)
	Standard Test Procedure for Polyphase Induction Motors and Generators	IEEE	IEEE 112-1996
	Motors and Generators	NEMA	NEMA MG 1-2003
	Energy Management Guide for Selection and Use of Fixed Frequency Medium AC Squirrel-Cage Polyphase Industrial Motors	NEMA	NEMA MG 10-2001
	Energy Management Guide for Selection and Use of Single-Phase Motors	NEMA	NEMA MG 11-1977 (R2001)
	Magnet Wire	NEMA	NEMA MW 1000-2003
	Motion/Position Control Motors, Controls, and Feedback Devices	NEMA	NEMA ICS 16-2000
	Electric Motors (1994)	UL	UL 1004
	Electric Motors and Generators for Use in Division 1 Hazardous (Classified) Locations (2003)	UL	ANSI/UL 674
	Overheating Protection for Motors (1997)	UL	ANSI/UL 2111
Pipe, Tubing, and Fittings	Scheme for the Identification of Piping Systems	ASME	ASME A13.1-1996 (RA02)
	Pipe Threads, General Purpose (Inch)	ASME	ANSI/ASME B1.20.1-1983 (RA01)
	Wrought Copper and Copper Alloy Braze-Joint Pressure Fittings	ASME	ASME B16.50-2001
	Power Piping	ASME	ASME B31.1-2004
	Fuel Gas Piping	ASME	ASME B31.2-1968

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Subject	Title	Publisher	Reference
	Process Piping	ASME	ASME B31.3-2004
	Refrigeration Piping and Heat Transfer Components	ASME	ASME B31.5-2001
	Building Services Piping	ASME	ASME B31.9-2004
	Practice for Obtaining Hydrostatic or Pressure Design Basis for "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe and Fittings	ASTM	ASTM D2992-01
	Specification for Welding of Austenitic Stainless Steel Tube and Piping Systems in Sanitary Applications	AWS	AWS D18.1:1999
	Standards of the Expansion Joint Manufacturers Association, 8th ed. (2003)	EJMA	EJMA
	Pipe Hangers and Supports—Materials, Design and Manufacture	MSS	MSS SP-58-2002
	Pipe Hangers and Supports—Selection and Application	MSS	ANSI/MSS SP-69-2003
	Welding Procedure Specifications	NCPWB	NCPWB
	International Fuel Gas Code	AGA/NFPA	ANSI Z223.1/NFPA 54-2006
	Refrigeration Tube Fittings—General Specifications	SAE	SAE J513-1999
	Seismic Restraint Manual—Guidelines for Mechanical Systems, 2nd ed.	SMACNA	ANSI/SMACNA 001-2000
	Tube Fittings for Flammable and Combustible Fluids, Refrigeration Service, and Marine Use (1997)	UL	ANSI/UL 109
Plastic	Specification for Acrylonitrile-Butadiene-Styrene (ABS) Plastic Pipe, Schedules 40 and 80	ASTM	ASTM D1527-99 E01
	Specification for Poly (Vinyl Chloride) (PVC) Plastic Pipe, Schedules 40, 80, and 120	ASTM	ASTM D1785-05
	Specification for Polyethylene (PE) Plastic Pipe, Schedule 40	ASTM	ASTM D2104-03
	Specification for Polybutylene (PB) Plastic Tubing	ASTM	ASTM D2666-96a
	Test Method for Obtaining Hydrostatic or Pressure Design Basis for Thermoplastic Pipe Products	ASTM	ASTM D2837-04
	Specification for Polybutylene (PB) Plastic Hot- and Cold-Water Distribution Systems	ASTM	ASTM D3309-96a (2002)
	Specification for Perfluoroalkoxy (PFA)-Fluoropolymer Tubing	ASTM	ASTM D6867-03
	Specification for Polyethylene Stay in Place Form System for End Walls for Drainage Pipe	ASTM	ASTM D7082-04
	Specification for Chlorinated Poly (Vinyl Chloride) (CPVC) Plastic Pipe, Schedules 40 and 80	ASTM	ASTM F441/F441M-02
	Specification for Crosslinked Polyethylene/Aluminum/Crosslinked Polyethylene Tubing OD Controlled SDR9	ASTM	ASTM F2262-05
	Test Method for Evaluating the Oxidative Resistance of Polyethylene (PE) Pipe to Chlorinated Water	ASTM	ASTM F2263-05
	Specification for 12 to 60 in. Annular Corrugated Profile-Wall Polyethylene (PE) Pipe and Fittings for Gravity-Flow Storm Sewer and Subsurface Drainage Applications	ASTM	ASTM F2306/F2306M-05
	Specification for Series 10 Poly (Vinyl Chloride) (PVC) Closed Profile Gravity Pipe and Fittings Based on Controlled Inside Diameter	ASTM	ASTM F2307-03
	Standard Test Method for Evaluating the Oxidative Resistance of Multilayer Polyolefin Tubing to Hot Chlorinated Water	ASTM	ASTM F2330-04
	Test Method for Determining Chemical Compatibility of Thread Sealants with Thermoplastic Threaded Pipe and Fittings Materials	ASTM	ASTM F2331-04
	Test Method for Determining Thermoplastic Pipe Wall Stiffness	ASTM	ASTM F2433-05
	Specification for Steel Reinforced Polyethylene (PE) Corrugated Pipe	ASTM	ASTM F2435-05
	Electrical Polyvinyl Chloride (PVC) Tubing and Conduit	NEMA	NEMA TC 2-2003
	PVC Plastic Utilities Duct for Underground Installation	NEMA	NEMA TC 6 and 8-2004
	Smooth-Wall Coilable Polyethylene Electrical Plastic Duct	NEMA	NEMA TC 7-2005
	Fittings for PVC Plastic Utilities Duct for Underground Installation	NEMA	NEMA TC 9-2004
	Electrical Nonmetallic Tubing (ENT)	NEMA	NEMA TC 13-2005
	Plastics Piping System Components and Related Materials	NSF	NSF/ANSI 14-2004
	Rubber Gasketed Fittings for Fire-Protection Service (2004)	UL	ANSI/UL 213
Metal	Welded and Seamless Wrought Steel Pipe	ASME	ASME B36.10M-2004
	Stainless Steel Pipe	ASME	ASME B36.19-2004
	Specification for Pipe, Steel, Black and Hot-Dipped, Zinc-Coated, Welded and Seamless	ASTM	ASTM A53/53M-05
	Specification for Seamless Carbon Steel Pipe for High-Temperature Service	ASTM	ASTM A106/A106M-04b
	Specification for Pipe, Steel, Electric-Fusion Arc-Welded Sizes NPS 16 and Over	ASTM	ASTM A1034-05b
	Specification for Steel Line Pipe, Black, Furnace-Butt-Welded	ASTM	ASTM A1037/A1037M-05
	Specification for Composite Corrugated Steel Pipe for Sewers and Drains	ASTM	ASTM A1042-04
	Specification for Seamless Copper Pipe, Standard Sizes	ASTM	ASTM B42-02e1
	Specification for Seamless Copper Tube	ASTM	ASTM B75-02
	Specification for Seamless Copper Water Tube	ASTM	ASTM B88-03
	Specification for Seamless Copper Tube for Air Conditioning and Refrigeration Field Service	ASTM	ASTM B280-03
	Specification for Hand-Drawn Copper Capillary Tube for Restrictor Applications	ASTM	ASTM B360-01
	Specification for Welded Copper Tube for Air Conditioning and Refrigeration Service	ASTM	ASTM B640-00
	Specification for Copper-Beryllium Seamless Tube UNS Nos. C17500 and C17510	ASTM	ASTM B0937-04

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Subject	Title	Publisher	Reference
	Test Method for Rapid Determination of Corrosiveness to Copper from Petroleum Products Using a Disposable Copper Foil Strip	ASTM	ASTM D7095-04
	Thickness Design of Ductile-Iron Pipe	AWWA	ANSI/AWWA C150/A21.50-02
	Fittings, Cast Metal Boxes, and Conduit Bodies for Conduit and Cable Assemblies	NEMA	NEMA FB 1-2003
	Polyvinyl-Chloride (PVC) Externally Coated Galvanized Rigid Steel Conduit and Intermediate Metal Conduit	NEMA	NEMA RN 1-2005
Plumbing	Backwater Valves	ASME	ASME A112.14.1-2003
	Plumbing Supply Fittings	ASME	ASME A112.18.1-2005
	Plumbing Waste Fittings	ASME	ASME A112.18.2-2005
	Performance Requirements for Backflow Protection Devices and Systems in Plumbing Fixture Fittings	ASME	ASME A112.18.3-2002
	Uniform Plumbing Code (2006) (with IAPMO Installation Standards)	IAPMO	IAPMO
	International Plumbing Code (2006)	ICC	IPC
	International Private Sewage Disposal Code (2006)	ICC	IPSDC
	2003 National Standard Plumbing Code (NSPC)	PHCC	NSPC 2003
	2003 National Standard Plumbing Code—Illustrated	PHCC	PHCC 2003
	Standard Plumbing Code (1997)	SBCCI	SPC
Pumps	Centrifugal Pumps	ASME	ASME PTC 8.2-1990
	Specification for Horizontal End Suction Centrifugal Pumps for Chemical Process	ASME	ASME B73.1-2001
	Specification for Vertical-in-Line Centrifugal Pumps for Chemical Process	ASME	ASME B73.2-2003
	Specification for Sealless Horizontal End Suction Metallic Centrifugal Pumps for Chemical Process	ASME	ASME B73.3-2003
	Specification for Thermoplastic and Thermoset Polymer Material Horizontal End Suction Centrifugal Pumps for Chemical Process	ASME	ASME B73.5M-1995 (RA01)
	Liquid Pumps	CSA	CAN/CSA-C.22.2 No. 108-01
	Energy Efficiency Test Methods for Small Pumps	CSA	CAN/CSA C820-02
	Performance Standard for Liquid Ring Vacuum Pumps, 3rd ed.	HEI	HEI 2005
	Centrifugal Pumps for Nomenclature and Definitions	HI	ANSI/HI 1.1-1.2 (2000)
	Centrifugal Pumps for Design and Applications	HI	ANSI/HI 1.3 (2000)
	Centrifugal Pumps for Installation, Operation, and Maintenance	HI	ANSI/HI 1.4 (2000)
	Vertical Pumps for Nomenclature and Definitions	HI	ANSI/HI 2.1-2.2 (2000)
	Vertical Pumps for Design and Application	HI	ANSI/HI 2.3 (2000)
	Vertical Pumps for Installation, Operation, and Maintenance	HI	ANSI/HI 2.4 (2000)
	Rotary Pumps for Nomenclature, Definitions, Application, and Operation	HI	ANSI/HI 3.1-3.5 (2000)
	Sealless Rotary Pumps for Nomenclature, Definitions, Application, Operation, and Test	HI	ANSI/HI 4.1-4.6 (2000)
	Sealless Centrifugal Pumps for Nomenclature, Definitions, Application, Operation, and Test	HI	ANSI/HI 5.1-5.6 (2000)
	Reciprocating Pumps for Nomenclature, Definitions, Application, and Operation	HI	ANSI/HI 6.1-6.5 (2000)
	Direct Acting (Steam) Pumps for Nomenclature, Definitions, Application, and Operation	HI	ANSI/HI 8.1-8.5 (2000)
	Pumps—General Guidelines for Types, Definitions, Application, Sound Measurement and Decontamination	HI	ANSI/HI 9.1-9.5 (2000)
	Centrifugal and Vertical Pumps for Allowable Nozzle Loads	HI	ANSI/HI 9.6.2 (2001)
	Centrifugal and Vertical Pumps for Allowable Operating Region	HI	ANSI/HI 9.6.3 (1997)
	Centrifugal and Vertical Pumps for Vibration Measurements and Allowable Values	HI	ANSI/HI 9.6.4 (2001)
	Centrifugal and Vertical Pumps for Condition Monitoring	HI	ANSI/HI 9.6.5 (2000)
	Pump Intake Design	HI	ANSI/HI 9.8 (1998)
	Engineering Data Book, 2nd ed.	HI	HI (1990)
	Circulation System Components and Related Materials for Swimming Pools, Spas/Hot Tubs	NSF	NSF/ANSI 50-2005
	Pumps for Oil-Burning Appliances (1997)	UL	UL 343
	Motor-Operated Water Pumps (2002)	UL	ANSI/UL 778
	Swimming Pool Pumps, Filters, and Chlorinators (1997)	UL	UL 1081
Radiators	Testing and Rating Standard for Baseboard Radiation, 8th ed. (2005)	HYDI	IBR
	Testing and Rating Standard for Finned Tube (Commercial) Radiation, 6th ed. (2005)	HYDI	IBR
Receivers	Refrigerant Liquid Receivers	ARI	ARI 495-2005
	Refrigerant-Containing Components and Accessories, Nonelectrical (2001)	UL	ANSI/UL 207
Refrigerants	Threshold Limit Values for Chemical Substances (updated annually)	ACGIH	ACGIH
	Specifications for Fluorocarbon Refrigerants	ARI	ARI 700-2004
	Refrigerant Recovery/Recycling Equipment	ARI	ARI 740-98
	Format for Information on Refrigerants	ASHRAE	ASHRAE *Guideline* 6-1996
	Method of Testing Flow Capacity of Refrigerant Capillary Tubes	ASHRAE	ANSI/ASHRAE 28-1996 (RA06)
	Designation and Safety Classification of Refrigerants	ASHRAE	ANSI/ASHRAE 34-2004
	Sealed Glass Tube Method to Test the Chemical Stability of Materials for Use Within Refrigerant Systems	ASHRAE	ANSI/ASHRAE 97-1999 (RA03)
	Refrigeration Oil Description	ASHRAE	ANSI/ASHRAE 99-2006

Selected Codes and Standards Published by Various Societies and Associations (*Continued*)

Subject	Title	Publisher	Reference
	Reducing the Release of Halogenated Refrigerants from Refrigerating and Air-Conditioning Equipment and Systems	ASHRAE	ANSI/ASHRAE 147-2002
	Test Method for Acid Number of Petroleum Products by Potentiometric Titration	ASTM	ASTM D664-06
	Test Method for Concentration Limits of Flammability of Chemical (Vapors and Gases)	ASTM	ASTM E681-04
	Refrigerant-Containing Components for Use in Electrical Equipment	CSA	C22.2 No. 140.3-M1987 (R2004)
	Refrigerants—Designation System	ISO	ISO 817:2005
	Procedure Retrofitting CFC-12 (R-12) Mobile Air-Conditioning Systems to HFC-134a (R-134a)	SAE	SAE J1661-1998
	Recommended Service Procedure for the Containment of CFC-12 (R-12)	SAE	SAE J1989-1998
	Standard of Purity for Recycled HFC-134a for Use in Mobile Air-Conditioning Systems	SAE	SAE J2099-1999
	HFC-134a (R-134a) Service Hose Fittings for Automotive Air-Conditioning Service Equipment	SAE	SAE J2197-1997
	Recommended Service Procedure for the Containment of HFC-134a	SAE	SAE J2211-1998
	HFC-134a (R-134a) Recovery/Recycling Equipment for Mobile Air-Conditioning Systems	SAE	SAE J2210-1999
	CFC-12 (R-12) Refrigerant Recovery Equipment for Mobile Automotive Air-Conditioning Systems	SAE	SAE J2209-1999
	Refrigerant-Containing Components and Accessories, Nonelectrical (2001)	UL	ANSI/UL 207
	Refrigerant Recovery/Recycling Equipment (2005)	UL	ANSI/UL 1963
	Field Conversion/Retrofit of Products to Change to an Alternative Refrigerant—Construction and Operation (1993)	UL	ANSI/UL 2170
	Field Conversion/Retrofit of Products to Change to an Alternative Refrigerant—Insulating Material and Refrigerant Compatibility (1993)	UL	ANSI/UL 2171
	Field Conversion/Retrofit of Products to Change to an Alternative Refrigerant—Procedures and Methods (1993)	UL	ANSI/UL 2172
	Refrigerants (1994)	UL	ANSI/UL 2182
Refrigeration	Safety Standard for Refrigeration Systems	ASHRAE	ANSI/ASHRAE 15-2004
	Mechanical Refrigeration Code	CSA	B52-05
	Refrigeration Equipment	CSA	CAN/CSA-C22.2 No. 120-M91 (R2004)
	Equipment, Design and Installation of Ammonia Mechanical Refrigerating Systems	IIAR	ANSI/IIAR 2-1999
	Refrigerated Medical Equipment (1993)	UL	ANSI/UL 416
Refrigeration Systems	Ejectors	ASME	ASME PTC 24-1976 (RA82)
	Reducing the Release of Halogenated Refrigerants from Refrigerating and Air-Conditioning Equipment and Systems	ASHRAE	ANSI/ASHRAE 147-2002
	Testing of Refrigerating Systems	ISO	ISO 916-1968
	Standards for Steam Jet Vacuum Systems, 5th ed.	HEI	HEI 2000
Transport	Mechanical Transport Refrigeration Units	ARI	ARI 1110-2001
	Mechanical Refrigeration and Air-Conditioning Installations Aboard Ship	ASHRAE	ANSI/ASHRAE 26-1996 (RA06)
	General Requirements for Application of Vapor Cycle Refrigeration Systems for Aircraft	SAE	SAE ARP731C-2003
	Safety Standard for Motor Vehicle Refrigerant Vapor Compression Systems	SAE	SAE J639-2005
Refrigerators	Method of Testing Commercial Refrigerators and Freezers	ASHRAE	ANSI/ASHRAE 72-2005
Commercial	Energy Performance Standard for Commercial Refrigerated Display Cabinets and Merchandise	CSA	C657-04
	Energy Performance Standard for Food Service Refrigerators and Freezers	CSA	C827-98 (R2003)
	Gas Food Service Equipment	CSA	ANSI Z83.11-2002/CSA 1.8A-2002
	Mobile Food Carts	NSF	NSF/ANSI 59-2002e
	Food Equipment	NSF	NSF/ANSI 2-2005a
	Commercial Refrigerators and Freezers	NSF	NSF/ANSI 7-2001
	Commercial Refrigerators and Freezers (1995)	UL	ANSI/UL 471
	Refrigerating Units (1994)	UL	ANSI/UL 427
	Refrigeration Unit Coolers (2004)	UL	ANSI/UL 412
Household	Household Refrigerators, Refrigerator-Freezers and Freezers	AHAM	ANSI/AHAM HRF-1-2004
	Refrigerators Using Gas Fuel	CSA	ANSI Z21.19-2002/CSA1.4-2002
	Energy Performance and Capacity of Household Refrigerators, Refrigerator-Freezers, and Freezers	CSA	CAN/CSA C300-00 (R2005)
	Household Refrigerators and Freezers (1993)	UL/CSA	ANSI/UL 250-1997/C22.2 No. 63-93
Retrofitting			
Building	Residential Duct Diagnostics and Repair (2003)	ACCA	ACCA
	Good HVAC Practices for Residential and Commercial Buildings (2003)	ACCA	ACCA
	Building Systems Analysis and Retrofit Manual, 1st ed.	SMACNA	SMACNA 1995
Refrigerant	Procedure for Retrofitting CFC-12 (R-12) Mobile Air Conditioning Systems to HFC-134a (R-134a)	SAE	SAE J1661-1998
	Field Conversion/Retrofit of Products to Change to an Alternative Refrigerant—Construction and Operation (1993)	UL	ANSI/UL 2170
	Field Conversion/Retrofit of Products to Change to an Alternative Refrigerant—Insulating Material and Refrigerant Compatibility (1993)	UL	ANSI/UL 2171

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Subject	Title	Publisher	Reference
	Field Conversion/Retrofit of Products to Change to an Alternative Refrigerant—Procedures and Methods (1993)	UL	ANSI/UL 2172
Roof Ventilators	Commercial Low Pressure, Low Velocity Duct System Design, 1st ed.	ACCA	ACCA Manual Q
	Power Ventilators (2004)	UL	ANSI/UL 705
Safety Devices	Bursting Discs and Bursting Disc Devices	ISO	ISO 6718:1991
Solar Equipment	Thermal Performance Testing of Solar Ambient Air Heaters	ASABE	ANSI/ASAE S423-2001
	Testing and Reporting Solar Cooker Performance	ASABE	ASAE S580-2003
	Method of Measuring Solar-Optical Properties of Materials	ASHRAE	ASHRAE 74-1988
	Methods of Testing to Determine the Thermal Performance of Solar Collectors	ASHRAE	ANSI/ASHRAE 93-2003
	Methods of Testing to Determine the Thermal Performance of Solar Domestic Water Heating Systems	ASHRAE	ANSI/ASHRAE 95-1987
	Methods of Testing to Determine the Thermal Performance of Unglazed Flat-Plate Liquid-Type Solar Collectors	ASHRAE	ANSI/ASHRAE 96-1980 (RA89)
	Methods of Testing to Determine the Thermal Performance of Flat-Plate Solar Collectors Containing a Boiling Liquid	ASHRAE	ANSI/ASHRAE 109-1986 (RA03)
	Practice for Installation and Service of Solar Space Heating Systems for One and Two Family Dwellings	ASTM	ASTM E683-91 (2001)
	Practice for Evaluating Thermal Insulation Materials for Use in Solar Collectors	ASTM	ASTM E861-94 (2001)
	Practice for Installation and Service of Solar Domestic Water Heating Systems for One and Two Family Dwellings	ASTM	ASTM E1056-85 (2001)
	Reference Solar Spectral Irradiance at the Ground at Different Receiving Conditions—Part 1: Direct Normal and Hemispherical Solar Irradiance for Air Mass 1.5	ISO	ISO 9845-1:1992
	Solar Collectors	CSA	CAN/CSA F378-87 (R2004)
	Solar Domestic Hot Water Systems (Liquid to Liquid Heat Transfer)	CSA	CAN/CSA F379-1.88 (R1999)
	Seasonal Use Solar Domestic Hot Water Systems	CSA	CAN/CSA F379.2-M89 (R1999)
	Installation Code for Solar Domestic Hot Water Systems	CSA	CAN/CSA F383-87 (R2003)
	Solar Heating—Domestic Water Heating Systems—Part 2: Outdoor Test Methods for System Performance Characterization and Yearly Performance Prediction of Solar-Only Systems	ISO	ISO 9459-2:1995
	Test Methods for Solar Collectors—Part 1: Thermal Performance of Glazed Liquid Heating Collectors Including Pressure Drop	ISO	ISO 9806-1:1994
	Part 2: Qualification Test Procedures	ISO	ISO 9806-2:1995
	Part 3: Thermal Performance of Unglazed Liquid Heating Collectors (Sensible Heat Transfer Only) Including Pressure Drop	ISO	ISO 9806-3:1995
	Solar Water Heaters—Elastomeric Materials for Absorbers, Connecting Pipes and Fittings—Method of Assessment	ISO	ISO 9808:1990
	Solar Energy—Calibration of a Pyranometer Using a Pyrheliometer	ISO	ISO 9846:1993
	Solar Heating—Swimming Pool Heating Systems—Dimensions, Design and Installation Guidelines	ISO	ISO 12596:1995
Solenoid Valves	Solenoid Valves for Use with Volatile Refrigerants	ARI	ARI 760-2001
	Methods of Testing Capacity of Refrigerant Solenoid Valves	ASHRAE	ANSI/ASHRAE 158.1-2004
	Electrically Operated Valves (1999)	UL	UL 429
Sound Measurement	Threshold Limit Values for Physical Agents (updated annually)	ACGIH	ACGIH
	Specification for Sound Level Meters	ASA	ANSI S1.4-1983 (R2001)
	Specification for Octave-Band and Fractional-Octave-Band Analog and Digital Filters	ASA	ANSI S1.11-2004
	Microphones, Part 1: Specifications for Laboratory Standard Microphones	ASA	ANSI S1.15-1997/Part 1 (R2001)
	Part 2: Primary Method for Pressure Calibration of Laboratory Standard Microphones by the Reciprocity Technique	ASA	ANSI S1.15-1997/Part 2
	Specification for Acoustical Calibrators	ASA	ANSI S1.40-1984 (R2001)
	Measurement of Industrial Sound	ASME	ASME PTC 36-2004
	Test Method for Measuring Acoustical and Airflow Performance of Duct Liner Materials and Prefabricated Silencers	ASTM	ASTM E477-05
	Test Method for Determination of Decay Rates for Use in Sound Insulation Test Methods	ASTM	ASTM E2235-04e01
	Sound and Vibration Design and Analysis (1994)	NEBB	NEBB
Fans	Reverberant Room Method for Sound Testing of Fans	AMCA	AMCA 300-05
	Methods for Calculating Fan Sound Ratings from Laboratory Test Data	AMCA	AMCA 301-05
	Application of Sone Ratings for Non-Ducted Air Moving Devices	AMCA	AMCA 302-73
	Application of Sound Power Level Ratings for Fans	AMCA	AMCA 303-79
	Acoustics—Measurement of Noise and Vibration of Small Air-Moving Devices—Part 1: Airborne Noise Emission	ASA	ANSI S12.11-2003/Part 1/ISO 10302:1996 (MOD)
	Part 2: Structure-Borne Vibration	ASA	ANSI S12.11-2003/Part 2
	Laboratory Method of Testing to Determine the Sound Power in a Duct	ASHRAE/AMCA	ANSI/ASHRAE 68-1997/AMCA 330-97
Other Equipment	Sound Rating of Outdoor Unitary Equipment	ARI	ARI 270-95
	Application of Sound Rating Levels of Outdoor Unitary Equipment	ARI	ARI 275-97

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Subject	Title	Publisher	Reference
	Sound Rating and Sound Transmission Loss of Packaged Terminal Equipment	ARI	ARI 300-2000
	Sound Rating of Non-Ducted Indoor Air-Conditioning Equipment	ARI	ARI 350-2000
	Sound Rating of Large Outdoor Refrigerating and Air-Conditioning Equipment	ARI	ARI 370-2001
	Method of Rating Sound and Vibration of Refrigerant Compressors	ARI	ARI 530-2005
	Method of Measuring Machinery Sound Within an Equipment Space	ARI	ARI 575-94
	Statistical Methods for Determining and Verifying Stated Noise Emission Values of Machinery and Equipment	ASA	ANSI S12.3-1985 (R2001)
	Sound Level Prediction for Installed Rotating Electrical Machines	NEMA	NEMA MG 3-1974 (R2003)
Techniques	Preferred Frequencies, Frequency Levels, and Band Numbers for Acoustical Measurements	ASA	ANSI S1.6-1984 (R2001)
	Reference Quantities for Acoustical Levels	ASA	ANSI S1.8-1989 (R2001)
	Measurement of Sound Pressure Levels in Air	ASA	ANSI S1.13-2005
	Procedure for the Computation of Loudness of Steady Sound	ASA	ANSI S3.4-2005
	Methods for Determining the Insertion Loss of Outdoor Noise Barriers	ASA	ANSI S12.8-1998 (R2003)
	Criteria for Evaluating Room Noise	ASA	ANSI S12.2-1995 (R1999)
	Engineering Method for the Determination of Sound Power Levels of Noise Sources Using Sound Intensity	ASA	ANSI S12.12-1992 (R2002)
	Procedures for Outdoor Measurement of Sound Pressure Level	ASA	ANSI S12.18-1994 (R2004)
	Guidelines for the Use of Sound Power Standards and for the Preparation of Noise Test Codes	ASA	ANSI S12.30-1990 (R2002)
	Precision Methods for the Determination of Sound Power Levels of Noise Sources in Anechoic and Hemi-Anechoic Rooms	ASA	ANSI S12.35-1990 (R2001)
	Methods for Measurement of Sound Emitted by Machinery and Equipment at Workstations and Other Specified Positions	ASA	ANSI S12.43-1997 (R2002)
	Methods for Calculation of Sound Emitted by Machinery and Equipment at Workstations and Other Specified Positions from Sound Power Level	ASA	ANSI S12.44-1997 (R2002)
	Acoustics—Determination of Sound Power Levels of Noise Sources Using Sound Pressure—Precision Method for Reverberation Rooms	ASA	ANSI S12.51-2002/ISO 3741:1999
	Acoustics—Determination of Sound Power Levels of Noise Sources—Engineering Methods for Small, Movable Sources in Reverberant Fields—Part 1: Comparison Method for Hard-Walled Test Rooms	ASA	ANSI S12.53/Part 1-1999 (R2004)/ISO 3743-1:1994
	Part 2: Methods for Special Reverberation Test Rooms	ASA	ANSI S12.53/Part 2-1999 (R2004)/ISO 3743-2:1994
	Acoustics—Determination of Sound Power Levels of Noise Sources Using Sound Pressure—Engineering Method in an Essentially Free Field over a Reflecting Plane	ASA	ANSI S12.54-1999 (R2004)/ISO 3744:1994
	Acoustics—Determination of Sound Power Levels of Noise Sources Using Sound Pressure—Survey Method Using an Enveloping Measurement Surface over a Reflecting Plane	ASA	ANSI S12.56-1999 (R2004)/ISO 3746:1995
	Test Method for Impedance and Absorption of Acoustical Materials by the Impedance Tube Method	ASTM	ASTM C384-04
	Test Method for Sound Absorption and Sound Absorption Coefficients by the Reverberation Room Method	ASTM	ASTM C423-02a
	Test Method for Measurement of Airborne Sound Insulation in Buildings	ASTM	ASTM E336-05
	Test Method for Impedance and Absorption of Acoustical Materials Using a Tube, Two Microphones and a Digital Frequency Analysis System	ASTM	ASTM E1050-98
	Test Method for Evaluating Masking Sound in Open Offices Using A-Weighted and One-Third Octave Band Sound Pressure Levels	ASTM	ASTM E1573-02
	Test Method for Measurement of Sound in Residential Spaces	ASTM	ASTM E1574-98
	Acoustics–Measurement of Sound Insulation in Buildings and of Building Elements; Part 1: Requirements for Laboratory Test Facilities with Suppressed Flanking Transmission	ISO	ISO 140-1:1997
	Part 4: Field Measurements of Airborne Sound Insulation Between Rooms	ISO	ISO 140-4:1998
	Part 5: Field Measurements of Airborne Sound Insulation of Facade Elements and Facades	ISO	ISO 140-5:1998
	Part 6: Laboratory Measurements of Impact Sound Insulation of Floors	ISO	ISO 140-6:1998
	Part 7: Field Measurements of Impact Sound Insulation of Floors	ISO	ISO 140-7:1998
	Part 8: Laboratory Measurements of the Reduction of Transmitted Impact Noise by Floor Coverings on a Heavyweight Standard Floor	ISO	ISO 140-8:1997
	Acoustics—Method for Calculating Loudness Level	ISO	ISO 532:1975
	Acoustics—Determination of Sound Power Levels of Noise Sources Using Sound Intensity; Part 1: Measurement at Discrete Points	ISO	ISO 9614-1:1993
	Part 2: Measurement by Scanning	ISO	ISO 9614-2:1996
	Procedural Standards for Measurement and Assessment of Sound and Vibration (1994)	NEBB	NEBB
Terminology	Acoustical Terminology	ASA	ANSI S1.1-1994 (R2004)
	Terminology Relating to Environmental Acoustics	ASTM	ASTM C 634-02
Space Heaters	Methods of Testing for Rating Combination Space-Heating and Water-Heating Appliances	ASHRAE	ANSI/ASHRAE 124-1991

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Subject	Title	Publisher	Reference
	Gas-Fired Room Heaters, Vol. II, Unvented Room Heaters	CSA	ANSI Z21.11.2-2002
	Vented Gas-Fired Space Heating Appliances	CSA	ANSI Z21.86-2004/CSA 2.32-2004
	Movable and Wall- or Ceiling-Hung Electric Room Heaters (2000)	UL	UL 1278
	Fixed and Location-Dedicated Electric Room Heaters (1997)	UL	UL 2021
Symbols	Graphic Electrical/Electronic Symbols for Air-Conditioning and Refrigerating Equipment	ARI	ARI 130-88
	Graphic Symbols for Heating, Ventilating, Air-Conditioning, and Refrigerating Systems	ASHRAE	ANSI/ASHRAE 134-2005
	Graphical Symbols for Plumbing Fixtures for Diagrams Used in Architecture and Building Construction	ASME	ANSI/ASME Y32.4-1977 (RA04)
	Symbols for Mechanical and Acoustical Elements as Used in Schematic Diagrams	ASME	ANSI/ASME Y32.18-1972 (RA03)
	Practice for Mechanical Symbols, Shipboard Heating, Ventilation, and Air Conditioning (HVAC)	ASTM	ASTM F856-97 (2004)
	Standard Symbols for Welding, Brazing, and Nondestructive Examination	AWS	AWS A2.4:1998
	Recommended Practice for the Preparation and Use of Symbols	IEEE	IEEE 267-1966
	Standard Letter Symbols for Quantities Used in Electrical Science and Electrical Engineering	IEEE	IEEE 280-1985 (R2003)
	Graphic Symbols for Electrical and Electronics Diagrams	IEEE	ANSI 315-1975 (R1993)/IEEE 315A-1986
	Standard for Logic Circuit Diagrams	IEEE	IEEE 991-1986 (R1994)
	Use of the International System of Units (SI): The Modern Metric System	IEEE/ASTM	IEEE/ASTM-SI10-2002
	Abbreviations and Acronyms	ASME	ASME Y14.38-1999
	Engineering Drawing Practices	ASME	ASME Y14.100-2004
	Safety Color Code	NEMA	ANSI/NEMA Z535-2002
Terminals, Wiring	Electrical Quick-Connect Terminals (2003)	UL	ANSI/UL 310
	Wire Connectors (2003)	UL	ANSI/UL 486A-486B
	Splicing Wire Connectors (2004)	UL	ANSI/UL 486C
	Equipment Wiring Terminals for Use with Aluminum and/or Copper Conductors (1994)	UL	ANSI/UL 486E
Testing and Balancing	AABC Commissioning Guideline (2002)	AABC	AABC
	AABC National Standards for Total System Balance (2002)	AABC	AABC
	Industrial Process/Power Generation Fans: Site Performance Test Standard	AMCA	AMCA 803-02
	Guidelines for Measuring and Reporting Environmental Parameters for Plant Experiments in Growth Chambers	ASABE	ANSI/ASAE EP411.4-2002
	The HVAC Commissioning Process	ASHRAE	ASHRAE *Guideline* 1-1996
	Practices for Measurement, Testing, Adjusting, and Balancing of Building Heating, Ventilation, Air-Conditioning, and Refrigeration Systems	ASHRAE	ANSI/ASHRAE 111-1988
	Practices for Measuring, Testing, Adjusting, and Balancing Shipboard HVAR&R Systems	ASHRAE	ANSI/ASHRAE 151-2002
	Centrifugal Pump Tests	HI	ANSI/HI 1.6 (2000)
	Vertical Pump Tests	HI	ANSI/HI 2.6 (2000)
	Rotary Pump Tests	HI	ANSI/HI 3.6 (2000)
	Reciprocating Pump Tests	HI	ANSI/HI 6.6 (2000)
	Pumps—General Guidelines for Types, Definitions, Application, Sound Measurement and Decontamination	HI	HI 9.1-9.5 (2000)
	Submersible Pump Tests	HI	ANSI/HI 11.6 (2001)
	Procedural Standards for Certified Testing of Cleanrooms, 2nd ed. (1996)	NEBB	NEBB
	Procedural Standards for Testing, Adjusting, Balancing of Environmental Systems, 7th ed. (2005)	NEBB	NEBB
	HVAC Systems Testing, Adjusting and Balancing, 3rd ed.	SMACNA	SMACNA 2002
Thermal Storage	Thermal Energy Storage—A Contractor's Tool Book	ACCA	ACCA
	Method of Testing Active Latent-Heat Storage Devices Based on Thermal Performance	ASHRAE	ANSI/ASHRAE 94.1-2002 (RA06)
	Method of Testing Thermal Storage Devices with Electrical Input and Thermal Output Based on Thermal Performance	ASHRAE	ANSI/ASHRAE 94.2-1981 (RA06)
	Method of Testing Active Sensible Thermal Energy Devices Based on Thermal Performance	ASHRAE	ANSI/ASHRAE 94.3-1986 (RA06)
	Practices for Measurement, Testing, Adjusting, and Balancing of Building Heating, Ventilation, Air-Conditioning, and Refrigeration Systems	ASHRAE	ANSI/ASHRAE 111-1988
	Method of Testing the Performance of Cool Storage Systems	ASHRAE	ANSI/ASHRAE 150-2000 (RA04)
Transformers	Minimum Efficiency Values for Liquid-Filled Distribution Transformers	CSA	CAN/CSA C802.1-00
	Minimum Efficiency Values for Dry-Type Transformers	CSA	CAN/CSA C802.2-00
	Maximum Losses For Power Transformers	CSA	CAN/CSA C802.3-01
	Guide for Determining Energy Efficiency of Distribution Transformers	NEMA	NEMA TP-1-2002
Turbines	Steam Turbines	ASME	ASME PTC 6-2004
	Steam Turbines for Combined Cycle	ASME	ASME PTC 6.2-2004
	Hydraulic Turbines and Pump-Turbines	ASME	ASME PTC 18-2002
	Gas Turbines	ASME	ASME PTC 22-1997 (RA03)
	Wind Turbines	ASME	ASME PTC 42-1988 (RA04)

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Subject	Title	Publisher	Reference
	Specification for Stainless Steel Bars for Compressor and Turbine Airfoils	ASTM	ASTM A1028-03
	Specification for Gas Turbine Fuel Oils	ASTM	ASTM D2880-03
	Land Based Steam Turbine Generator Sets	NEMA	NEMA SM 24-1991 (R2002)
	Steam Turbines for Mechanical Drive Service	NEMA	NEMA SM 23-1991 (R2002)
Valves	Face-to-Face and End-to-End Dimensions of Valves	ASME	ASME B16.10-2000 (R03)
	Pressure Relief Devices	ASME	ASME PTC 25-2001
	Valves—Flanged, Threaded, and Welding End	ASME	ASME B16.34-2004
	Manually Operated Metallic Gas Valves for Use in Aboveground Piping Systems up to 5 psi	ASME	ASME B16.44-2002
	Methods of Testing Capacity of Refrigerant Solenoid Valves	ASHRAE	ANSI/ASHRAE 158.1-2004
	Relief Valves for Hot Water Supply	CSA	ANSI Z21.22-1999 (R2003)/ CSA 4.4-M99 (R2004)
	Control Valve Capacity Test Procedures	ISA	ANSI/ISA-S75.02-1996
	Flow Equations for Sizing Control Valves	ISA	ANSI/ISA-S75.01.01-2002
	Industrial Valves—Part-Turn Actuator Attachments	ISO	ISO 5211-1:2001
	Metal Valves for Use in Flanged Pipe Systems—Face-to-Face and Centre-to-Face Dimensions	ISO	ISO 5752:1982
	Safety Valves for Protection Against Excessive Pressure, Part 1: Safety Valves	ISO	ISO 4126-1:1991
	Oxygen System Fill/Check Valve	SAE	SAE AS1225A-1997
	Valves for Anhydrous Ammonia and LP-Gas (Other Than Safety Relief) (1997)	UL	ANSI/UL 125
	Safety Relief Valves for Anhydrous Ammonia and LP-Gas (1997)	UL	ANSI/UL 132
	LP-Gas Regulators (1999)	UL	ANSI/UL 144
	Electrically Operated Valves (1999)	UL	UL 429
	Valves for Flammable Fluids (1997)	UL	ANSI/UL 842
Gas	Manually Operated Metallic Gas Valves for Use in Gas Piping Systems up to 125 psig (Sizes NPS 1/2 through 2)	ASME	ASME B16.33-2002
	Large Metallic Valves for Gas Distribution (Manually Operated, NPS-2 1/2 to 12, 125 psig Maximum)	ASME	ANSI/ASME B16.38-1985 (RA05)
	Manually Operated Thermoplastic Gas Shutoffs and Valves in Gas Distribution Systems	ASME	ASME B16.40-2002
	Manually Operated Gas Valves for Appliances, Appliance Connection Valves, and Hose End Valves	CSA	ANSI Z21.15-1997 (R2003)/CGA 9.1-M97
	Automatic Valves for Gas Appliances	CSA	ANSI Z21.21-2005/CGA 6.5-2005
	Combination Gas Controls for Gas Appliances	CSA	ANSI Z21.78-2005/CGA 6.20-2005
	Convenience Gas Outlets and Optional Enclosures	CSA	ANSI Z21.90-2001/CSA 6.24-2001
Refrigerant	Refrigerant Access Valves and Hose Connectors	ARI	ARI 720-2002
	Thermostatic Refrigerant Expansion Valves	ARI	ARI 750-2001
	Solenoid Valves for Use with Volatile Refrigerants	ARI	ARI 760-2001
	Refrigerant Pressure Regulating Valves	ARI	ARI 770-2001
Vapor Retarders	Practice for Selection of Vapor Retarders for Thermal Insulation	ASTM	ASTM C755-03
	Practice for Determining the Properties of Jacketing Materials for Thermal Insulation	ASTM	ASTM C921-03a
	Specification for Flexible, Low Permeance Vapor Retarders for Thermal Insulation	ASTM	ASTM C1136-03a
	Test Method for Water Vapor Transmission Rate of Flexible Barrier Materials Using an Infrared Detection Technique	ASTM	ASTM F372-99 (2003)
Vending Machines	Methods of Testing for Rating Vending Machines for Bottled, Canned, and Other Sealed Beverages	ASHRAE	ANSI/ASHRAE 32.1-2004
	Methods of Testing for Rating Pre-Mix and Post Mix Beverage Dispensing Equipment	ASHRAE	ANSI/ASHRAE 32.2-2003
	Vending Machines	CSA	C22.2 No.128-95 (R2004)
	Energy Performance of Vending Machines	CSA	CAN/CSA C804-96 (R2001)
	Vending Machines for Food and Beverages	NSF	NSF/ANSI 25-2005
	Vending Machines (1995)	UL	ANSI/UL 751
	Refrigerated Vending Machines (1995)	UL	ANSI/UL 541
Vent Dampers	Automatic Vent Damper Devices for Use with Gas-Fired Appliances	CSA	ANSI Z21.66-1996 (R2001)/CSA 6.14-M96
	Vent or Chimney Connector Dampers for Oil-Fired Appliances (1994)	UL	ANSI/UL 17
Ventilation	Commercial Applications, Systems, and Equipment, 1st ed.	ACCA	ACCA Manual CS
	Commercial Low Pressure, Low Velocity Duct System Design, 1st ed.	ACCA	ACCA Manual Q
	Comfort, Air Quality, and Efficiency by Design	ACCA	ACCA Manual RS
	Guide for Testing Ventilation Systems (1991)	ACGIH	ACGIH
	Industrial Ventilation: A Manual of Recommended Practice, 25th ed. (2004)	ACGIH	ACGIH
	Design of Ventilation Systems for Poultry and Livestock Shelters	ASABE	ASAE EP270.5-2003
	Design Values for Emergency Ventilation and Care of Livestock and Poultry	ASABE	ANSI/ASAE EP282.2-2004
	Heating, Ventilating and Cooling Greenhouses	ASABE	ANSI/ASAE EP406.4-2003
	Guidelines for Selection of Energy Efficient Agricultural Ventilation Fans	ASABE	ASAE EP566-2001
	Uniform Terminology for Livestock Production Facilities	ASABE	ASAE S501-2001

Selected Codes and Standards Published by Various Societies and Associations (*Continued*)

Subject	Title	Publisher	Reference
	Agricultural Ventilation Constant Speed Fan Test Standard	ASABE	ASABE S565-2005
	Ventilation for Acceptable Indoor Air Quality	ASHRAE	ANSI/ASHRAE 62.1-2004
	Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings	ASHRAE	ANSI/ASHRAE 62.2-2004
	Method of Testing for Room Air Diffusion	ASHRAE	ANSI/ASHRAE 113-2005
	Measuring Air Change Effectiveness	ASHRAE	ANSI/ASHRAE 129-1997 (RA02)
	Method of Determining Air Change Rates in Detached Dwellings	ASHRAE	ANSI/ASHRAE 136-1993 (RA06)
	Ventilation for Commercial Cooking Operations	ASHRAE	ANSI/ASHRAE 154-2003
	Residential Mechanical Ventilation Systems	CSA	CAN/CSA F326-M91 (R2005)
	Parking Structures	NFPA	NFPA 88A-02
	Installation of Air Conditioning and Ventilating Systems	NFPA	NFPA 90A-02
	Ventilation Control and Fire Protection of Commercial Cooking Operations	NFPA	NFPA 96-04
	Food Equipment	NSF	NSF/ANSI 2-2005a
	Class II (Laminar Flow) Biosafety Cabinetry	NSF	NSF/ANSI 49-2004a
	Aerothermodynamic Systems Engineering and Design	SAE	SAE AIR1168/3-1989
	Heater, Airplane, Engine Exhaust Gas to Air Heat Exchanger Type	SAE	SAE ARP86A-1996
	Test Procedure for Battery Flame Retardant Venting Systems	SAE	SAE J1495-2005
Venting	Commercial Applications, Systems, and Equipment, 1st ed.	ACCA	ACCA Manual CS
	Draft Hoods	CSA	ANSI Z21.12-1990 (R2000)
	National Fuel Gas Code	AGA/NFPA	ANSI Z223.1/NFPA 54-2006
	Explosion Prevention Systems	NFPA	NFPA 69-02
	Smoke and Heat Venting	NFPA	NFPA 204-02
	Chimneys, Fireplaces, Vents and Solid Fuel-Burning Appliances	NFPA	NFPA 211-06
	Guide for Steel Stack Construction, 2nd ed.	SMACNA	SMACNA 1996
	Draft Equipment (1993)	UL	UL 378
	Gas Vents (1996)	UL	ANSI/UL 441
	Type L Low-Temperature Venting Systems (1995)	UL	ANSI/UL 641
Vibration	Balance Quality and Vibration Levels for Fans	AMCA	ANSI/AMCA 204-05
	Techniques of Machinery Vibration Measurement	ASA	ANSI S2.17-1980 (R2004)
	Vibrations of Buildings—Guidelines for the Measurement of Vibrations and Evaluation of Their Effects on Buildings	ASA	ANSI S2.47-1990 (R2001)
	Mechanical Vibration and Shock—Resilient Mounting Systems—Part 1: Technical Information to Be Exchanged for the Application of Isolation Systems	ASA	ISO 2017-1:2005
	Evaluation of Human Exposure to Whole-Body Vibration—Part 2: Vibration in Buildings (1 Hz to 80 Hz)	ISO	ISO 2631-2:2003
	Guidelines for the Evaluation of the Response of Occupants of Fixed Structures, Especially Buildings and Off-Shore Structures, to Low-Frequency Horizontal Motion (0.063 to 1 Hz)	ISO	ISO 6897:1984
	Procedural Standards for Measurement and Assessment of Sound and Vibration (1994)	NEBB	NEBB
	Sound and Vibration Design and Analysis (1994)	NEBB	NEBB
Water Heaters	Desuperheater/Water Heaters	ARI	ARI 470-2001
	Safety for Electrically Heated Livestock Waterers	ASABE	ASAE EP342.2-1995 (R2005)
	Methods of Testing to Determine the Thermal Performance of Solar Domestic Water Heating Systems	ASHRAE	ANSI/ASHRAE 95-1987
	Method of Testing for Rating Commercial Gas, Electric, and Oil Service Water Heating Equipment	ASHRAE	ANSI/ASHRAE 118.1-2003
	Method of Testing for Rating Residential Water Heaters	ASHRAE	ANSI/ASHRAE 118.2-2006
	Methods of Testing for Rating Combination Space-Heating and Water-Heating Appliances	ASHRAE	ANSI/ASHRAE 124-1991
	Methods of Testing for Efficiency of Space-Conditioning/Water-Heating Appliances That Include a Desuperheater Water Heater	ASHRAE	ANSI/ASHRAE 137-1995 (RA04)
	Boiler and Pressure Vessel Code—Section IV: Heating Boilers	ASME	BPVC-2004
	Section VI: Recommended Rules for the Care and Operation of Heating Boilers	ASME	BPVC-2004
	Gas Water Heaters—Vol. I: Storage Water Heaters with Input Ratings of 75,000 Btu per Hour or Less	CSA	ANSI Z21.10.1-2004/CSA 4.1-2004
	Vol. III: Storage, with Input Ratings Above 75,000 Btu per Hour, Circulating and Instantaneous Water Heaters	CSA	ANSI Z21.10.3-2004/CSA 4.3-2004
	Oil Burning Stoves and Water Heaters	CSA	B140.3-1962 (R2001)
	Oil-Fired Service Water Heaters and Swimming Pool Heaters	CSA	B140.12-03
	Construction and Test of Electric Storage-Tank Water Heaters	CSA	CAN/CSA-C22.2 No. 110-94 (R2004)
	Performance of Electric Storage Tank Water Heaters for Household Service	CSA	C191-04
	Energy Efficiency of Electric Storage Tank Water Heaters and Heat Pump Water Heaters	CSA	CSA C745-03
	One Time Use Water Heater Emergency Shut-Off	IAPMO	IGC 175-2003
	Water Heaters, Hot Water Supply Boilers, and Heat Recovery Equipment	NSF	NSF/ANSI 5-2005
	Oil-Fired Storage Tank Water Heaters (1995)	UL	ANSI/UL 732
	Commercial-Industrial Gas Heating Equipment (1999)	UL	UL 795

Selected Codes and Standards Published by Various Societies and Associations (*Continued*)

Subject	Title	Publisher	Reference
	Electric Booster and Commercial Storage Tank Water Heaters (2004)	UL	ANSI/UL 1453
	Household Electric Storage Tank Water Heaters (2004)	UL	ANSI/UL 174
Welding and Brazing	Boiler and Pressure Vessel Code—Section IX: Welding and Brazing Qualifications	ASME	BPVC-2004
	Structural Welding Code—Steel	AWS	AWS D1.1/D1.1M:2006
	Specification for Welding of Austenitic Stainless Steel Tube and Piping Systems in Sanitary Applications	AWS	AWS D18.1:1999
Wood-Burning Appliances	Threshold Limit Values for Chemical Substances (updated annually)	ACGIH	ACGIH
	Specification for Room Heaters, Pellet Fuel Burning Type	ASTM	ASTM E1509-04
	Guide for Construction of Solid Fuel Burning Masonry Heaters	ASTM	ASTM E1602-03
	Installation Code for Solid-Fuel-Burning Appliances and Equipment	CSA	CAN/CSA-B365-01
	Solid-Fuel-Fired Central Heating Appliances	CSA	CAN/CSA-B366.1-M91 (R2002)
	Chimneys, Fireplaces, Vents, and Solid Fuel-Burning Appliances	NFPA	ANSI/NFPA 211-06
	Commercial Cooking, Rethermalization and Powered Hot Food Holding and Transport Equipment	NSF	NSF/ANSI 4-2005e

ORGANIZATIONS

Abbrev.	Organization	Address	Telephone	http://www.
AABC	Associated Air Balance Council	1518 K Street NW, Suite 503 Washington, D.C. 20005	(202) 737-0202	aabchq.com
ABMA	American Boiler Manufacturers Association	8221 Old Courthouse Road, Suite 207 Vienna, VA 22182	(703) 356-7171	abma.com
ACCA	Air Conditioning Contractors of America	2800 Shirlington Road, Suite 300 Arlington, VA 22206	(703) 575-4477	acca.org
ACGIH	American Conference of Governmental Industrial Hygienists	1330 Kemper Meadow Drive Cincinnati, OH 45240	(513) 742-2020	acgih.org
ADC	Air Diffusion Council	1901 North Roselle Road, Suite 800 Schaumburg, IL 60195	(847) 706-6750	flexibleduct.org
AGA	American Gas Association	400 N. Capitol Street NW, Suite 400 Washington, D.C. 20001	(202) 824-7000	aga.org
AHAM	Association of Home Appliance Manufacturers	1111 19th Street NW, Suite 402 Washington, D.C. 20036	(202) 872-5955	aham.org
AIHA	American Industrial Hygiene Association	2700 Prosperity Avenue, Suite 250 Fairfax, VA 22031	(703) 849-8888	aiha.org
AMCA	Air Movement and Control Association International	30 West University Drive Arlington Heights, IL 60004-1893	(847) 394-0150	amca.org
ANSI	American National Standards Institute	1819 L Street NW, 6th Floor Washington, D.C. 20036	(202) 293-8020	ansi.org
ARI	Air-Conditioning and Refrigeration Institute	4100 North Fairfax Drive, Suite 200 Arlington, VA 22203	(703) 524-8800	ari.org
ASA	Acoustical Society of America	2 Huntington Quadrangle, Suite 1NO1 Melville, NY 14747-4502	(516) 576-2360	asa.aip.org
ASABE	American Society of Agricultural and Biological Engineers	2950 Niles Road St. Joseph, MI 49085-9659	(269) 429-0300	asabe.org
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers	1791 Tullie Circle, NE Atlanta, GA 30329	(404) 636-8400	ashrae.org
ASME	ASME	3 Park Avenue New York, NY 10016-5990	(973) 882-1167	asme.org
ASTM	ASTM International	100 Barr Harbor Drive, P.O. Box C700 West Conshohocken, PA 19428-2959	(610) 832-9500	astm.org
AWS	American Welding Society	550 N.W. LeJeune Road Miami, FL 33126	(305) 443-9353	aws.org
AWWA	American Water Works Association	6666 W. Quincy Avenue Denver, CO 80235	(303) 794-7711	awwa.org
BOCA	Building Officials and Code Administrators International	(*see* ICC)		
BSI	British Standards Institution	389 Chiswick High Road London W4 4AL, UK	44(0)20-8996-9001	bsi-global.com
CAGI	Compressed Air and Gas Institute	1300 Sumner Avenue Cleveland, OH 44115-2851	(216) 241-7333	cagi.org
CSA	Canadian Standards Association International	5060 Spectrum Way Mississauga, ON L4W 5N6, Canada	(416) 747-4000	csa.ca
	Also available from CSA America	8501 East Pleasant Valley Road Cleveland, OH 44131-5575	(216) 524-4990	csa-america.org
CTI	Cooling Technology Institute	P.O. Box 73383 Houston, TX 77273-3383	(281) 583-4087	cti.org
EJMA	Expansion Joint Manufacturers Association	25 North Broadway Tarrytown, NY 10591	(914) 332-0040	ejma.org
HEI	Heat Exchange Institute	1300 Sumner Avenue Cleveland, OH 44115-2815	(216) 241-7333	heatexchange.org
HI	Hydraulic Institute	9 Sylvan Way Parsippany, NJ 07054-3802	(973) 267-9700	pumps.org
HYDI	Hydronics Institute Division of GAMA	2107 Wilson Boulevard, Suite 600 Arlington, VA 22201	(703) 525-7060	gamanet.org
IAPMO	International Association of Plumbing and Mechanical Officials	5001 E. Philadelphia Street Ontario, CA 91761-2816	(909) 472-4100	iapmo.org

ORGANIZATIONS (*Continued*)

Abbrev.	Organization	Address	Telephone	http://www.
ICBO	International Conference of Building Officials	(*see* ICC)		
ICC	International Code Council	500 New Jersey Ave NW, 6th Floor Washington, D.C. 20001	(888) 422-7233	iccsafe.org
IEEE	Institute of Electrical and Electronics Engineers	45 Hoes Lane Piscataway, NJ 08854-4141	(732) 981-0060	ieee.org
IESNA	Illuminating Engineering Society of North America	120 Wall Street, Floor 17 New York, NY 10005-4001	(212) 248-5000	iesna.org
IFCI	International Fire Code Institute	(*see* ICC)		
IIAR	International Institute of Ammonia Refrigeration	1110 North Glebe Road, Suite 250 Arlington, VA 22201	(703) 312-4200	iiar.org
ISA	The Instrumentation, Systems, and Automation Society	67 Alexander Drive, P.O. Box 12777 Research Triangle Park, NC 27709	(919) 549-8411	isa.org
ISO	International Organization for Standardization	1, ch. de la Voie-Creuse, Case postale 56 CH-1211 Geneva 20, Switzerland	41-22-749-01 11	iso.org
MCAA	Mechanical Contractors Association of America	1385 Piccard Drive Rockville, MD 20850	(301) 869-5800	mcaa.org
MICA	Midwest Insulation Contractors Association	16712 Elm Circle Omaha, NE 68130	(800) 747-6422	micainsulation.org
MSS	Manufacturers Standardization Society of the Valve and Fittings Industry	127 Park Street NE Vienna, VA 22180-4602	(703) 281-6613	mss-hq.com
NAIMA	North American Insulation Manufacturers Association	44 Canal Center Plaza, Suite 310 Alexandria, VA 22314	(703) 684-0084	naima.org
NCPWB	National Certified Pipe Welding Bureau	1385 Piccard Drive Rockville, MD 20850-4340	(301) 869-5800	mcaa.org/ncpwb
NCSBCS	National Conference of States on Building Codes and Standards	505 Huntmar Park Drive, Suite 210 Herndon, VA 20170	(703) 437-0100	ncsbcs.org
NEBB	National Environmental Balancing Bureau	8575 Grovemont Circle Gaithersburg, MD 20877	(301) 977-3698	nebb.org
NEMA	National Electrical Manufacturers Association	1300 North 17th Street, Suite 1752 Rosslyn, VA 22209	(703) 841-3200	nema.org
NFPA	National Fire Protection Association	1 Batterymarch Park Quincy, MA 02169-7471	(617) 770-3000	nfpa.org
NRCC	National Research Council of Canada, Institute for Research in Construction	1200 Montreal Road, Bldg M-58 Ottawa, ON K1A 0R6, Canada	(877) 672-2672	nrc-cnrc.ca
NSF	NSF International	P.O. Box 130140, 789 N. Dixboro Road Ann Arbor, MI 48113-0140	(734) 769-8010	nsf.org
PHCC	Plumbing-Heating-Cooling Contractors National Association	180 S. Washington Street, P.O. Box 6808 Falls Church, VA 22046	(703) 237-8100	phccweb.org
SAE	Society of Automotive Engineers International	400 Commonwealth Drive Warrendale, PA 15096-0001	(724) 776-4841	sae.org
SBCCI	Southern Building Code Congress International	(*see* ICC)		
SMACNA	Sheet Metal and Air Conditioning Contractors' National Association	4201 Lafayette Center Drive Chantilly, VA 20151-1209	(703) 803-2980	smacna.org
TEMA	Tubular Exchanger Manufacturers Association	25 North Broadway Tarrytown, NY 10591	(914) 332-0040	tema.org
UL	Underwriters Laboratories	333 Pfingsten Road Northbrook, IL 60062-2096	(847) 272-8800	ul.com

ASHRAE HANDBOOK

Additions and Corrections

This report includes additional information, and technical errors found between June 15, 2004, and March 29, 2007, in the inch-pound (I-P) editions of the 2004, 2005, and 2006 *ASHRAE Handbook* volumes. Occasional typographical errors and nonstandard symbol labels will be corrected in future volumes. The most current list of Handbook additions and corrections is on the ASHRAE Web site (www.ashrae.org).

The authors and editor encourage you to notify them if you find other technical errors. Please send corrections to: Handbook Editor, ASHRAE, 1791 Tullie Circle NE, Atlanta, GA 30329, or e-mail mowen@ashrae.org.

2004 HVAC Systems and Equipment

p. 2.5, Fig. 8. The caption for Figure 8 should read "Chemical Dehumidification."

p. 8.5, Fig. 5. The top two figures, for air/air and water/air refrigerant changeover, were cut off and are provided here.

p. 12.9, Fig. 16. The figure for reverse-return two-pipe systems was incorrect; the corrected version is provided here.

p. 20.4. Under Additional Moisture Losses, the reference should be to Chapter 12, not Chapter 11.

p. 25.4, Eq. (5). There should be an equals symbol after D_{pc}.

p. 35.19, 1st col., 4th line from bottom. Change "Chapters 35 and 38 of this volume" to "Chapter 38 of this volume."

p. 36.3, Fig. 4. The figure was partially cut off; it is supplied in complete form on p. A.2.

p. 44.3-44.4, Example 1, Solution. Correct the following values: $h_1 = 30.6$, $h_3 = 28.15$, and $w_3 = 0.0093$. Thus, $w_2 = 0.0082$ lb/lb, $w_4 = 0.0082$ lb/lb, $q_L = -799$ Btu/min, and $q = 785$ Btu/min. In the last paragraph in the example, change 0.00795 to 0.0082, change 21.9 to 29.4, and change "to be" to "is."

p. 44.10, Fig. 5. Replace with the correct figure, provided on p. A.2.
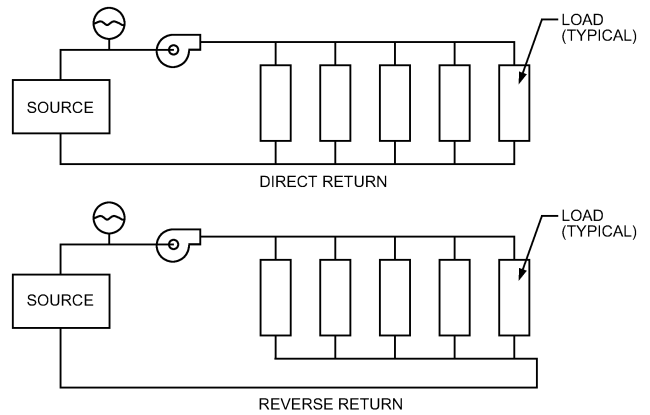
Fig. 16   Direct- and Reverse-Return Two-Pipe Systems
(2004 HVAC Systems and Equipment, Ch. 12, p. 9)

Heat Source and Sink	Distribution Fluid	Thermal Cycle	Diagram
Air	Air	Refrigerant changeover	
Water	Air	Refrigerant changeover	
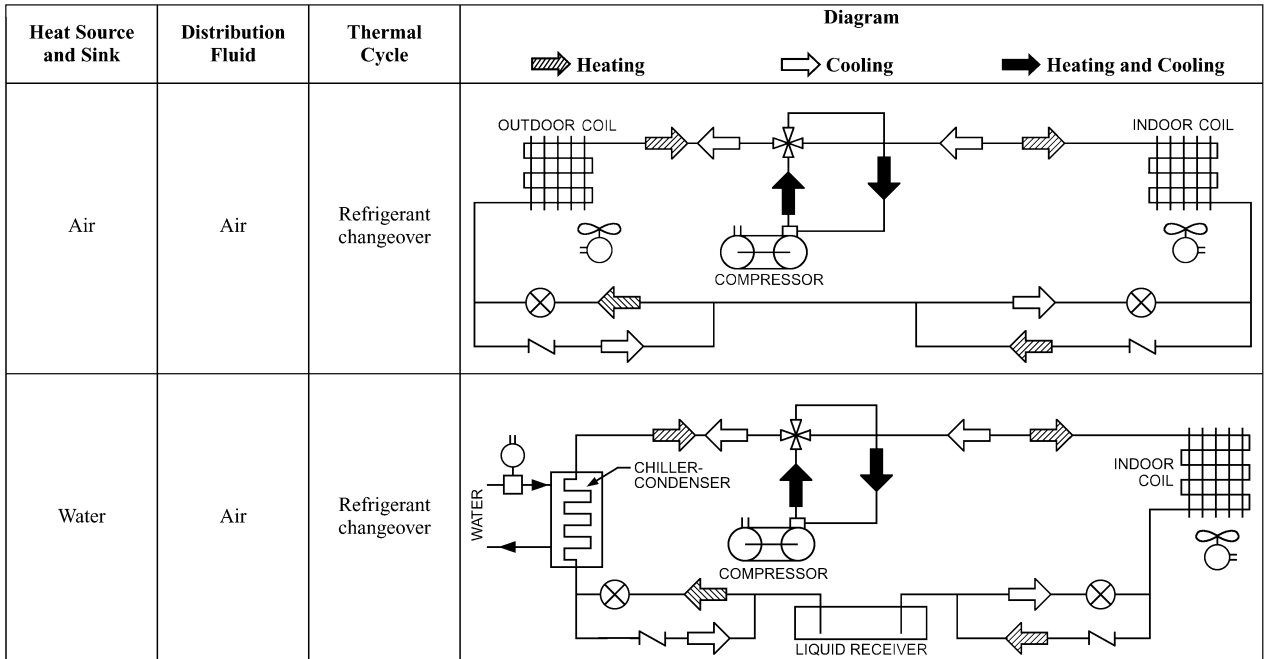
Fig. 5   Heat Pump Types (first two rows)
(2004 HVAC Systems and Equipment, Ch. 8, p. 5)
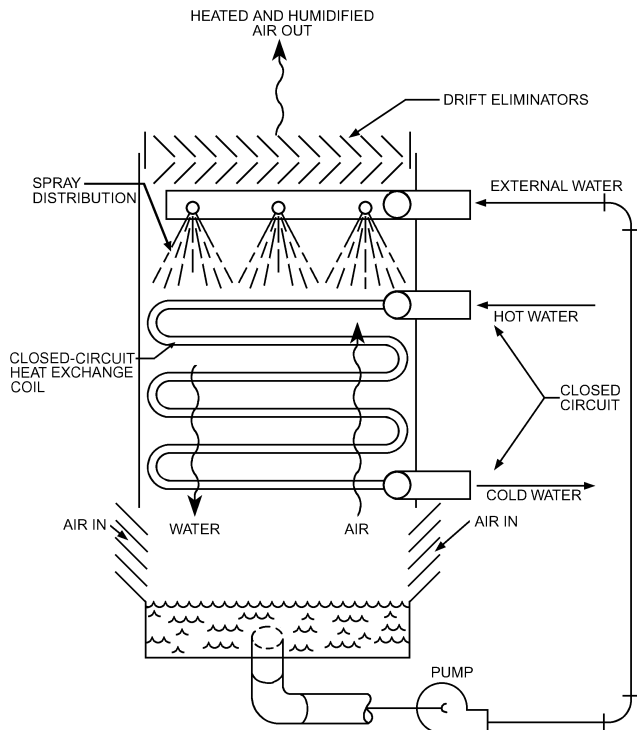
Fig. 4   Indirect-Contact or Closed-Circuit Evaporative Cooling Tower
(2004 HVAC Systems and Equipment, Chapter 36, p. 3)

p. 44.19, Example 4, Step 7. The reference to Figure 17 should be to Figure 19.

p. 44.19, Example 5. Correct the following values: $h_3 = 23.7$ and $w_3 = 0.0052$. Thus, $h_4 = 13.43$ Btu/lb, $t_4 = 35.7°F$, $w_4 = 0.0044$ lb/lb, $m_w = 38.4$ lb/h, and $q_e = 505,900$ Btu/h.

pp. 44.19-44.20, Example 6. Correct the following values: $h_1 = 44.6$ Btu/lb, $w_1 = 0.0198$ lb/lb, $h_3 = 28.5$ Btu/lb, and $w_3 = 0.0096$ lb/lb. Thus, q_{max} (total) = 566,000 Btu/h, $q_t = 321,000$, $q_{lat} = 203,000$ Btu/h, $h_2 = 35.5$ Btu/lb, $t_{w2} = 71.6°F$, $t_4 = 86.2°F$, $h_4 = 35.4$ Btu/lb, $w_4 = 0.0134$, and $t_{w4} = 71.6°F$. In step 6, second equation, $q_t = 319,000$ Btu/h.

pp. 44.20-44.21, Example 7, Solution. Correct the following values: $h_1 = 44.6$ Btu/lb, $w_1 = 0.0198$ lb/lb, $h_3 = 28.5$ Btu/lb, and $w_3 = 0.0096$ lb/lb. Thus, $h_2 = 33.16$ Btu/lb, $w_2 = 0.0129$, $t_{w2} = 69.2°F$, $h_4 = 39.5$ Btu/lb, and $t_{w4} = 76.1°F$. In step 6, second equation, $q_t = 41,460$ Btu/h.

pp. 44.22-44.23, Example 9, Solution. In step 5a, entering enthalpy should be 44.6 Btu/lb. Thus, $h_s = 38.6$ Btu/lb; two lines below this equation, change the wet-bulb temperature for saturated air to 75°F. In step 5b, entering enthalpy is 21.3 Btu/lb; thus, $h_4 = 27.3$ Btu/lb.

p. 44.25, Bibliography. The correct entry for the ASHRAE (1974) source is as follows:

ASHRAE. 1974. Symposium on heat recovery. *ASHRAE Transactions* 80(1):302-332.

Index. The following chapter references are correct for these entries:

EFFECTIVENESS

——— SENSIBLE   —·—·— LATENT   ········ TOTAL   ——·—— PRESSURE DROP
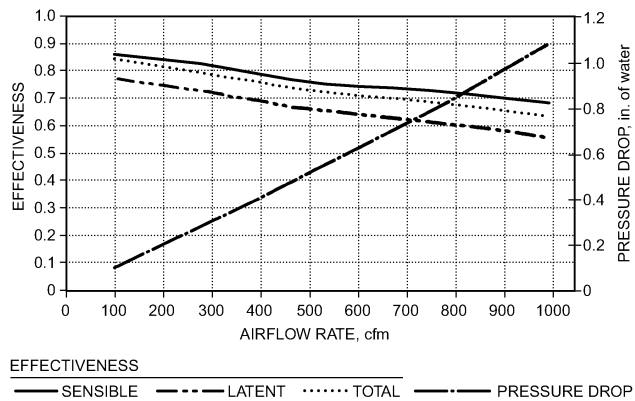
Fig. 5   Variation of Pressure Drop and Effectiveness with Air Flow Rates for a Membrane Plate Exchanger
(2004 HVAC Systems and Equipment, Ch. 44, p. 10)

2005 Fundamentals

p. 1.17, Eq. (63). $\dot{Q}_{evap}$ should be $\dot{Q}_{cond}$.

p. 1.20, Symbols. Units for V should be ft/s.

p. 2.7, Table 2. Values for ε (right column) should be 60, 1800, 6000, and 10,200 μin.

p. 2.11, definitions for Eq. (38). In the definition for Δh, there should be parentheses around $p_1 - p_2$.

p. 3.1, definitions for Eq. (1a). Units for thermal conductivity k should be Btu/h·ft·°F.

p. 3.2, Thermal Conduction, 2nd line from bottom. Change "steady" to "steady-state."

p. 3.5, Eq. (10). The equation should be as follows:

$$c_1 = \frac{2\,\mathrm{Bi}}{(\mu_1^2 + \mathrm{Bi}^2)\,J_0(\mu_1)}$$

p. 3.13, 1st col. Delete first repeated paragraph after Equation (30).

p. 3.21, 2nd col., last full sentence. Change to, "Depending on frequency and amplitude of vibration, forced convection from a wire to air is enhanced by up to 300% (Nesis et al. 1994)."

p. 3.28, Eq. (44). Delete second equals sign and second fraction.

p. 7.20, 1st col., last full paragraph. Change third sentence to read, "the resonance frequency of the system is maintained at 3.13 Hz, and the force transmitted to the structure remains at 12.5 lb$_f$." Change sixth sentence to read, "where a is acceleration, the maximum dynamic displacement of the mounted equipment is reduced by a factor of (M_1/M_2), where M_1 and M_2 are the masses before and after mass is added, respectively."

p. 15.3, Eq. (3) and following text. Change K_a to K_d in the equation, definitions, and following paragraph (three places total).

Table 7 Comparative Refrigerant Performance per Ton of Refrigeration
(2005 Fundamentals, Ch. 19, p. 8)

No.	Chemical Name or Composition (% by mass)	Evaporator Pressure, psia	Condenser Pressure, psia	Compression Ratio	Net Refrigerating Effect, Btu/lb	Refrigerant Circulated, lb/min	Liquid Circulated, gal/min	Specific Volume of Suction Gas, ft³/lb	Compressor Displacement, ft³/min	Power Consumption, hp	Coefficient of Performance	Compressor Discharge Temp., °F
170	Ethane	233.2	672.8	2.88	69.5	2.85	1.22	0.541	1.54	1.72	2.70	121.73
744	Carbon dioxide	326.9	1041.4	3.19	57.3	1.79	0.36	0.269	0.48	0.91	2.69	157.73
1270	Propylene	51.9	189.1	3.64	123.0	1.62	0.39	2.081	3.37	1.04	4.50	107.33
290	Propane	41.5	155.9	3.76	119.5	1.65	0.41	2.502	4.13	1.03	4.50	96.53
502	R-22/115 (48.8/51.2)	49.7	190.3	3.83	45.6	4.40	0.44	0.814	3.58	1.08	4.38	100.13
507A	R-125/143a (50/50)	55.0	211.6	3.85	47.4	4.22	0.50	0.814	3.44	1.13	4.18	94.73
404A	R-125/143a/134a (44/52/4)	52.9	206.0	3.89	49.1	4.08	0.48	0.860	3.51	1.12	4.21	96.53
410A	R-32/125 (50/50)	69.3	271.5	3.92	72.2	2.71	0.31	0.873	2.37	1.05	4.41	123.53
125	Pentafluoroethane	58.5	226.4	3.87	36.7	5.31	0.55	0.631	3.35	1.15	3.99	87.53
22	Chlorodifluoromethane	42.8	172.2	4.02	69.9	2.85	0.29	1.248	3.56	1.01	4.66	127.13
12	Dichlorodifluoromethane	26.3	107.5	4.09	50.3	3.94	0.37	1.479	5.83	1.00	4.70	100.13
500	R-12/152a (73.8/26.2)	31.0	127.1	4.09	60.1	3.31	0.35	1.504	4.98	1.00	4.66	105.53
407C	R-32/125/134a (23/25/52)	41.8	182.7	4.38	70.2	2.85	0.30	1.289	3.67	1.05	4.50	118.13
600a	Isobutane*	12.8	58.5	4.58	113.5	1.76	0.39	6.524	11.48	1.01	4.62	85.73
134a	Tetrafluoroethane	23.6	111.2	4.71	63.6	3.13	0.31	1.945	6.09	1.02	4.60	98.33
124	Chlorotetrafluoroethane*	12.8	64.3	5.03	50.7	3.90	0.35	2.741	10.69	1.01	4.62	85.73
717	Ammonia	34.1	168.5	4.94	474.3	0.42	0.08	8.197	3.44	1.00	4.76	209.93
600	Butane*	8.1	41.0	5.05	125.6	1.65	0.35	10.325	17.04	1.03	4.74	85.73
11	Trichlorofluoromethane	2.9	18.1	6.25	67.0	2.95	0.24	12.317	36.34	0.93	5.02	109.13
123	Dichlorotrifluoroethane	2.3	15.8	6.81	61.2	3.27	0.27	14.279	46.69	0.96	4.90	91.13
113	Trichlorotrifluoroethane*	1.0	7.8	7.71	52.7	3.66	0.28	26.940	98.60	0.94	4.81	85.73

*Superheat required.

p. 16.11, Symbols. Add the following definitions:

h_s = exhaust stack height (typically above roof unless otherwise specified), ft (see Figure 3, and Chapter 44 in the 2003 *ASHRAE Handbook—HVAC Applications*)

S = stretched-string distance; shortest distance from exhaust to intake over obstacles and along building surface, ft [see Figure 3, and Equation (22) in the 2003 *ASHRAE Handbook—HVAC Applications*]

p. 19.8, Table 7. Replace the table with the one supplied here.

p. 23.6, Fig. 1. Change caption from "Adsorption Isotherms" to "Typical Adsorption."

p. 26.3, Eq. (2). The correct equation is

$$R_T = 12 \ln(D_3/D_2)/(2\pi k)$$

p. 27.14, Figure 9. Air leakage should be at 0.2 in. of water.

p. 28.2, Table 1 (and all data tables), cols. 13a, c, and e. Because of a data processing error, the enthalpy values in these columns are systematically low by 7.687 Btu/lb. Thus, all enthalpy values in Table 1 and in all design climatic condition tables on the accompanying CD-ROM should be increased by that amount.

p. 29.8, Table 7. Units for OF_b should be °F.

p. 29.9, Table 9. The correct numbers for the last line of the table are as follows:

E_t 326   325   321   314   305   293   279   262   243

p. 29.9, Eq. (23). Units for CF_{slab} should be Btu/h·ft²; 0.51 is a constant with units of Btu/h·ft²; and 2.5 is a factor with units of °F.

p. 30.2, 2nd col., 6th para., last line. Change "with" to "without."

p. 30.4, bottom of 2nd col. The reference to Equation (3) should be to Equation (4).

p. 30.27, Table 19. Footnote 7 should refer to Table 3 in Chapter 39.

p. 30.32, Central Plant, Piping. The cross reference should be to Chapter 26, not Chapter 23.

p. 30.34, Part 1, Solution. In the equations, change all "1500 W" to "440 W" (1500 is correct for the solutions for q_7 to q_{18}).

p. 31.6, Table 2. In the footnote for Winter Conditions, add the following: $h_i = h_{ic} + h_{iR} = 0.30(\Delta T/L)^{0.25} + \varepsilon\Gamma(T_i^4 - T_g^4)/\Delta T$, where $\Delta T = T_i - T_g$, °R; L = glazing height, ft; T_g = glass temperature, °R.

p. 31.26, Table 13. For ID 1b, change the following values:

T	0.77	0.75	0.73	0.68	0.58	0.35	0.69
R^f	0.07	0.08	0.09	0.13	0.24	0.48	0.13
R^b	0.07	0.08	0.09	0.13	0.24	0.48	0.13

p. 31.40, Table 16, last two rows, center column. Change "0.42" to "0.16," and "0.44" to "0.10."

p. 32.5, 1st col. Cross references to the following equations in Chapter 30 should be as follows (the chapter number should stay the same; only the equation numbers should be updated):

Equation (36)	Equation (27)
Equation (35)	Equation (26)
Equation (34)	Equation (25)

p. 38.1, 1st col. The definition of an acre should be 43,560 ft^2. The conversion factor for ft of water to Pa should be 2989.

p. 40.26. The URL for CSA America should be csa-america.org.

2006 Refrigeration

(None.)

COMPOSITE INDEX
ASHRAE HANDBOOK SERIES

This index covers the current Handbook series published by ASHRAE. The four volumes in the series are identified as follows:

S = 2004 HVAC Systems and Equipment

F = 2005 Fundamentals

R = 2006 Refrigeration

A = 2007 HVAC Applications

Alphabetization of the index is letter by letter; for example, **Heaters** precedes **Heat exchangers**, and **Floors** precedes **Floor slabs**.

The page reference for an index entry includes the book letter and the chapter number, which may be followed by a decimal point and the beginning page in the chapter. For example, the page number S31.4 means the information may be found in the 2004 HVAC Systems and Equipment volume, Chapter 31, beginning on page 4.

Each Handbook volume is revised and updated on a four-year cycle. Because technology and the interests of ASHRAE members change, some topics are not included in the current Handbook series but may be found in the earlier Handbook editions cited in the index.

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