CHAPTER 1
REFRIGERATION CYCLES

1. OBJECTIVE

- Introduce the concepts of refrigerators and heat pumps and the measure of their performance.
- Analyze the ideal vapor-compression refrigeration cycle.
- Analyze the actual vapor-compression refrigeration cycle.
- Review the factors involved in selecting the right refrigerant for an application.
- Discuss the operation of refrigeration and heat pump systems.
- Evaluate the performance of innovative vapor-compression refrigeration systems.
- Analyze gas refrigeration systems.
- Introduce the concepts of absorption-refrigeration systems.

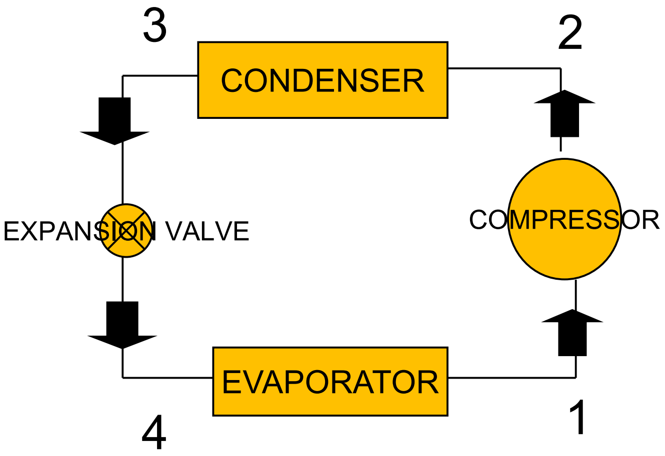
PRINCIPLES OF REFRIGERATION

Refrigeration means to cool an object below its surrounding temperature

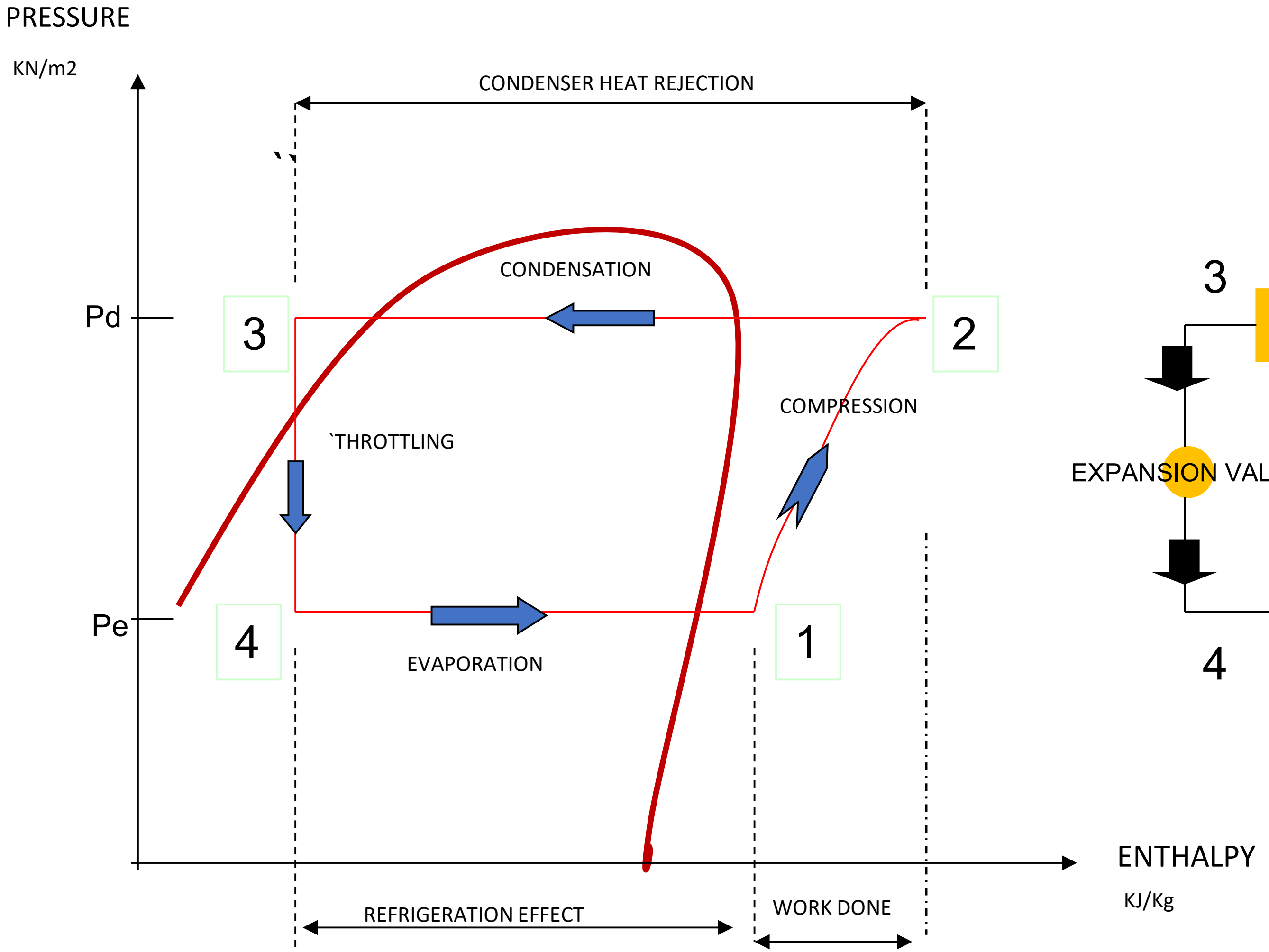
1. VAPOUR COMPRESSION CYCLE

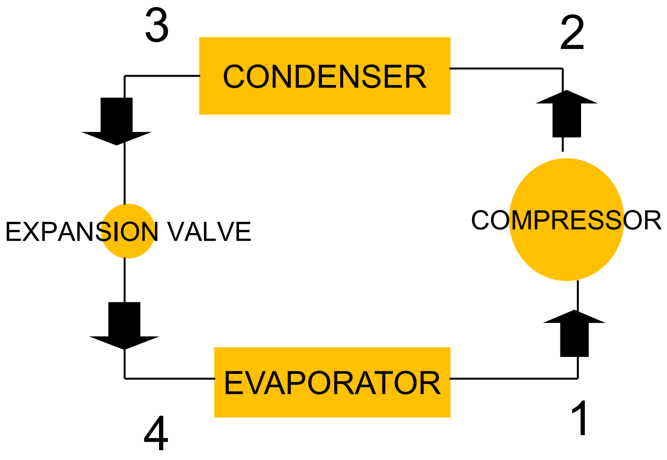
Basic components of the vapour compression refrigeration system

- Compressor
- Condenser
- Throttling Device
- Evaporator

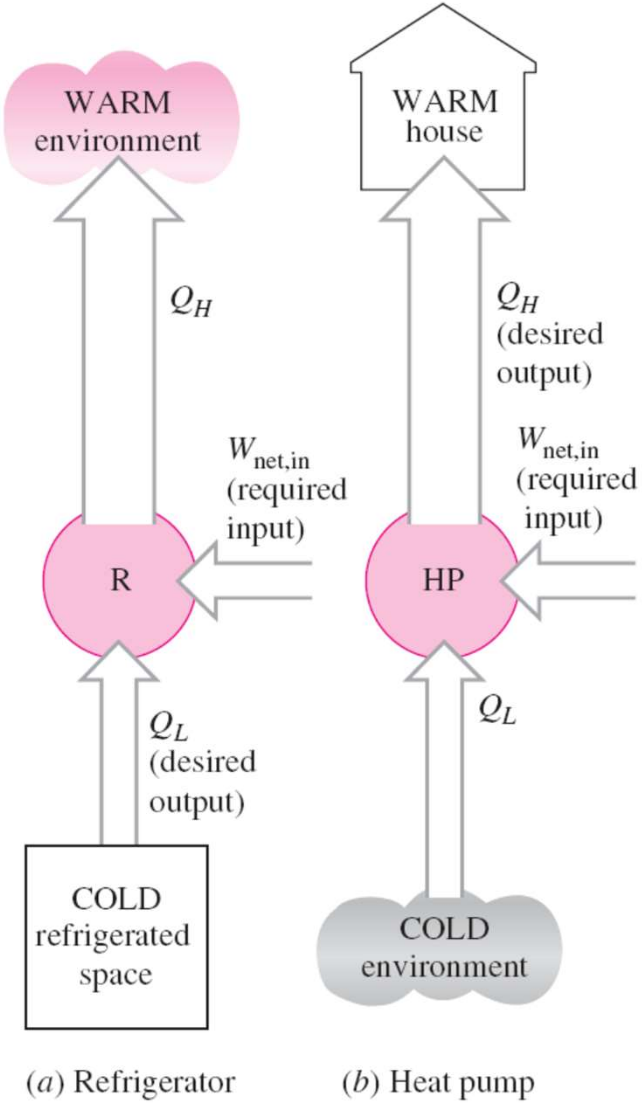


Vapour Compression Cycle





REVIEW ON REFIGERATION



(*a*) Refrigerator (*b*) Heat pump

The transfer of heat from a low-temperature region to a high-temperature one requires special devices called **refrigerators**.

Refrigerators and heat pumps are essentially the same devices; they differ in their objectives only.

$$\text{COP}_\text{R} = \frac{\text{Desired output}}{\text{Required input}} = \frac{\text{Cooling effect}}{\text{Work input}} = \frac{Q_L}{W_{\text{net,in}}}$$

$$\text{COP}_\text{HP} = \frac{\text{Desired output}}{\text{Required input}} = \frac{\text{Heating effect}}{\text{Work input}} = \frac{Q_H}{W_{\text{net,in}}}$$

$\text{COP}_\text{HP} = \text{COP}_\text{R} + 1$ for fixed values of Q_L and Q_H

The objective of a refrigerator is to remove heat (Q_L) from the cold medium; the objective of a heat pump is to supply heat (Q_H) to a warm medium.

Unit of Refrigeration

The unit of refrigeration is kW or TR

TON OF REFRIGERATION (TR)

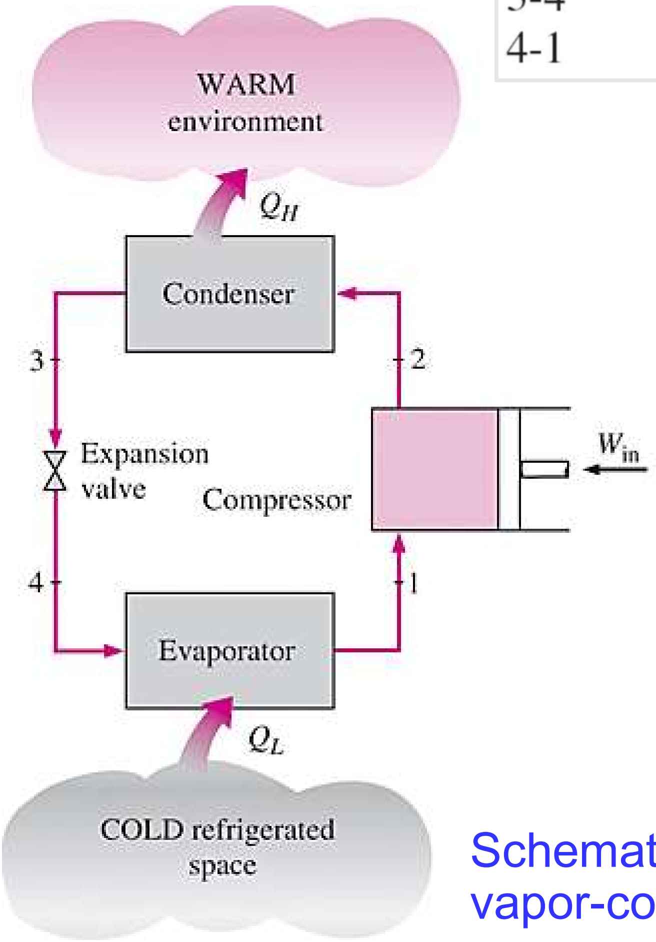
1 TR = 12’000 Btu/hr BRITISH UNITS

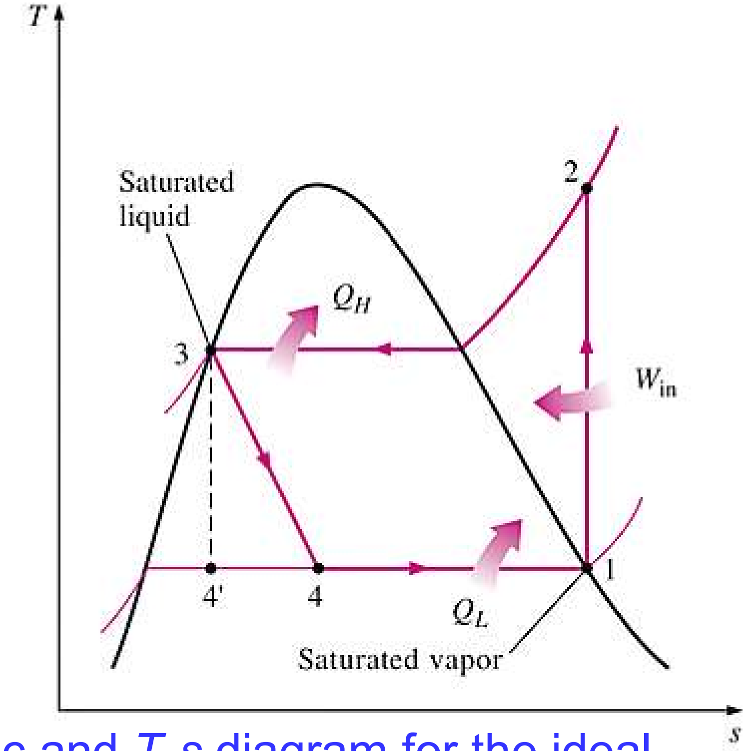
1 TR = 3.517 KW SI UNITS

THE IDEAL VAPOR-COMPRESSION REFRIGERATION CYCLE

The **vapor-compression refrigeration cycle** is the ideal model for refrigeration systems. Unlike the reversed Carnot cycle, the refrigerant is vaporized completely before it is compressed and the turbine is replaced with a throttling device.

1-2	Isentropic compression in a compressor
2-3	Constant-pressure heat rejection in a condenser
3-4	Throttling in an expansion device
4-1	Constant-pressure heat absorption in an evaporator

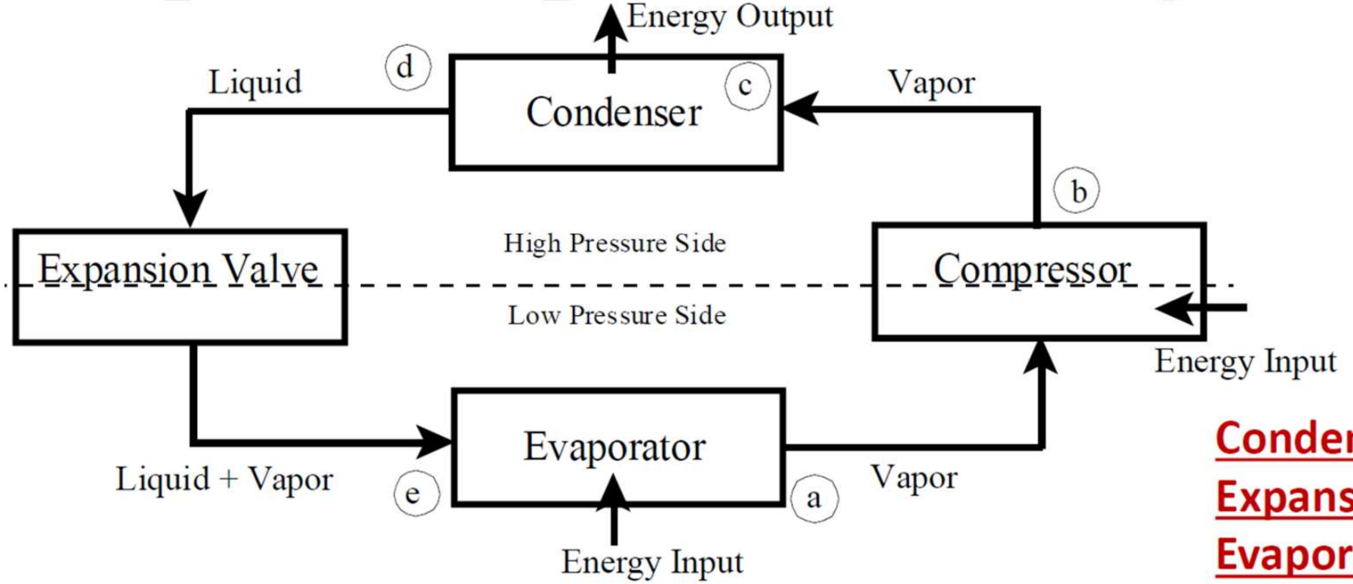




Schematic and T-s diagram for the ideal vapor-compression refrigeration cycle.

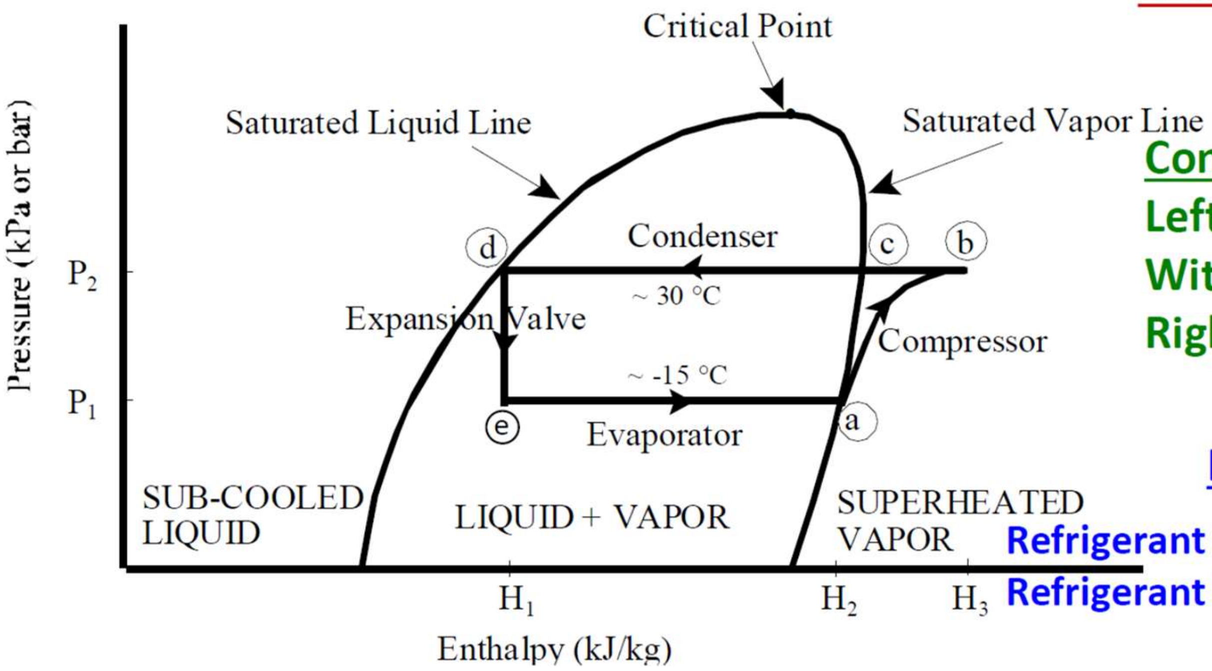
This is the most widely used cycle for refrigerators, A-C systems, and heat pumps.

Vapor Compression Refrigeration System



IDEAL CONDITIONS

Condensing: Constant Pr. (P_2)
Expansion: Constant Enthalpy (H_1)
Evaporation: Constant Pr. (P_1)
Compression: Constant Entropy (S



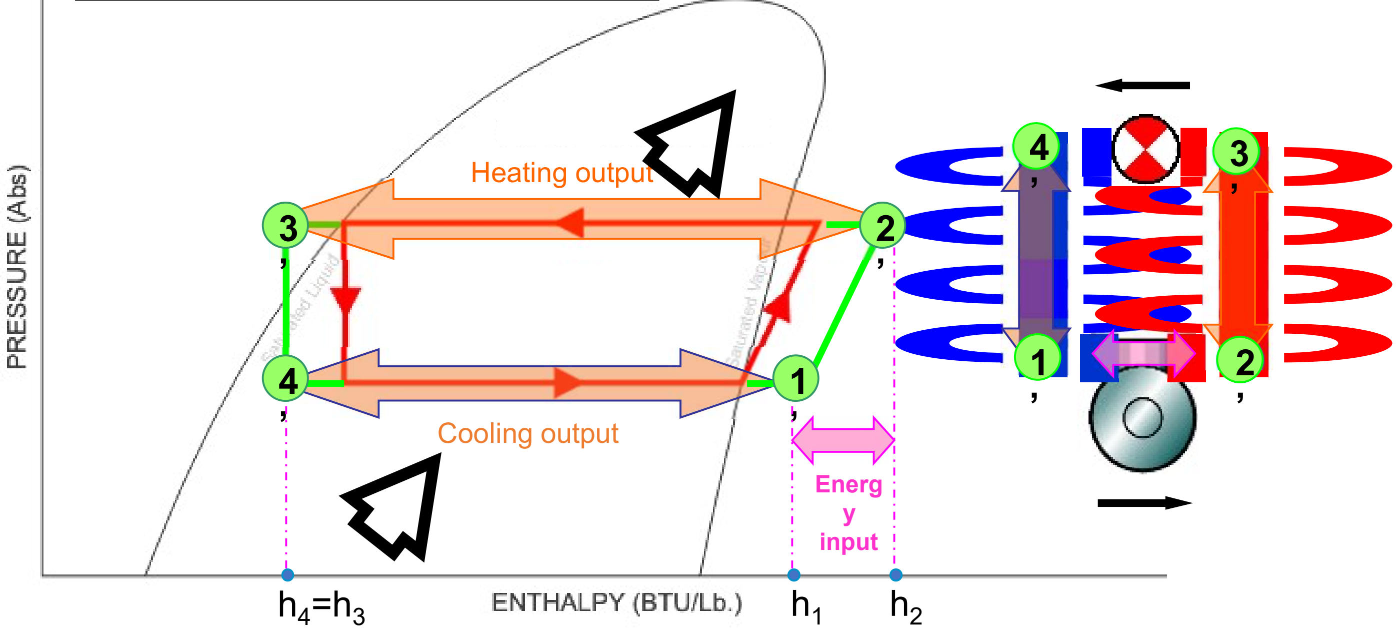
Constant Temperature Line
Left of dome: Vertical
Within dome: Horizontal
Right of dome: Curved down

IDEAL CONDITIONS

Refrigerant is 100% vapor at end of evap. AND
Refrigerant is 100% liquid at end of condenser

The Refrigeration Cycle on p-h Chart

$$\text{COP} = \frac{\text{Coolingg output } (h_2\text{-}h_4)}{\text{Total energy input } (h_2\text{-}h_1)}$$



Functions of Components of a Vapor Compression Refrigeration System

- Evaporator
  - Extract heat from the product/air and use it as the latent heat of vaporization of the refrigerant
- Compressor
  - Raise temperature of refrigerant to well above that of surroundings to facilitate transfer of energy to surroundings in condenser
- Condenser
  - Transfer energy from the refrigerant to the surroundings (air/water)
  - Slightly sub-cool the refrigerant to minimize amount of vapor generated as it passes through the expansion valve
- Expansion valve
  - Serve as metering device for flow of refrigerant
  - Expand the liquid refrigerant from the compressor pressure to the evaporator pressure (with minimal conversion to vapor)

The ideal vapor-compression refrigeration cycle involves an irreversible (throttling) process to make it a more realistic model for the actual systems.

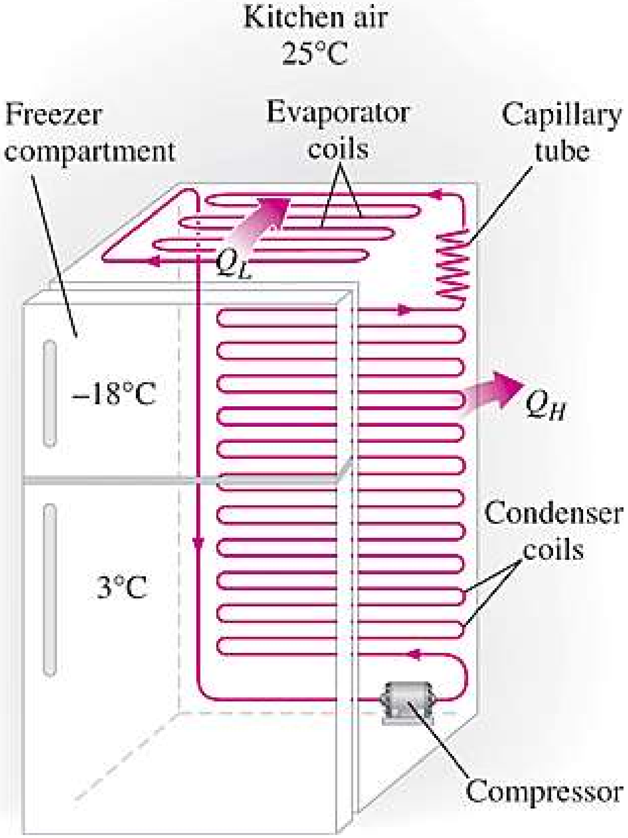
Replacing the expansion valve by a turbine is not practical since the added benefits cannot justify the added cost and complexity.

Steady-flow energy balance $(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_e - h_i$

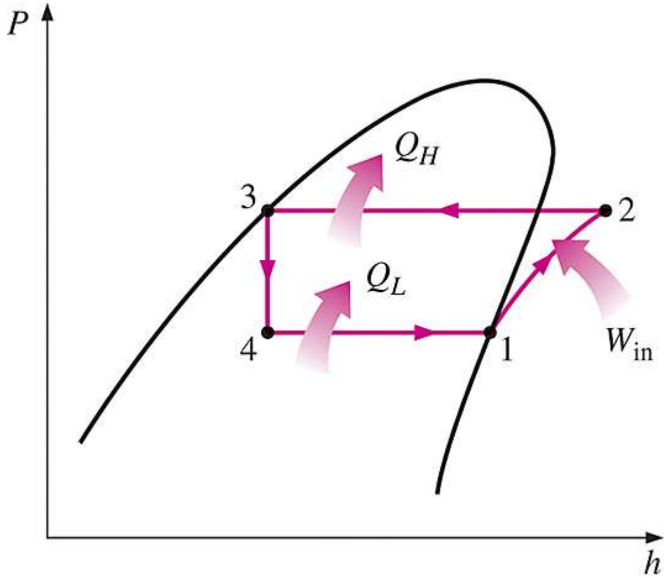
$$\mathrm{COP_R} = \frac{q_L}{w_{\mathrm{net,in}}} = \frac{h_1 - h_4}{h_2 - h_1}$$

$$\mathrm{COP_{HP}} = \frac{q_H}{w_{\mathrm{net,in}}} = \frac{h_2 - h_3}{h_2 - h_1}$$

$h_1 = h_{g\,@\,P_1}$ and $h_3 = h_{f\,@\,P_3}$ for the ideal case



An ordinary household refrigerator.



The *P-h* diagram of an ideal vapor-compression refrigeration cycle.

Refrigeration Cycle Efficiency

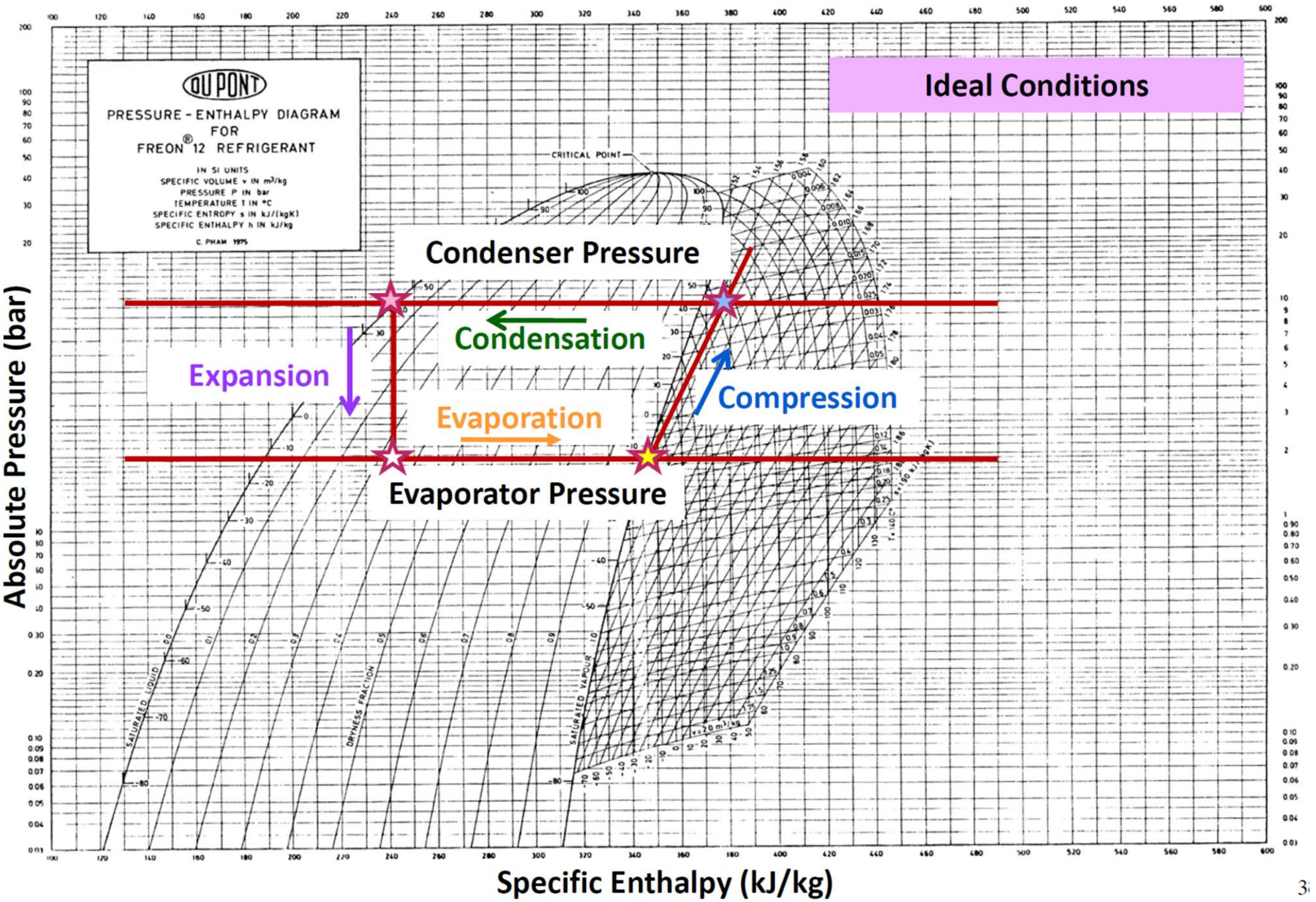
The refrigeration cycle efficiency is known as

COEFFICIENT OF PERFORMANCE (COP$_{\mathrm{REF}}$)

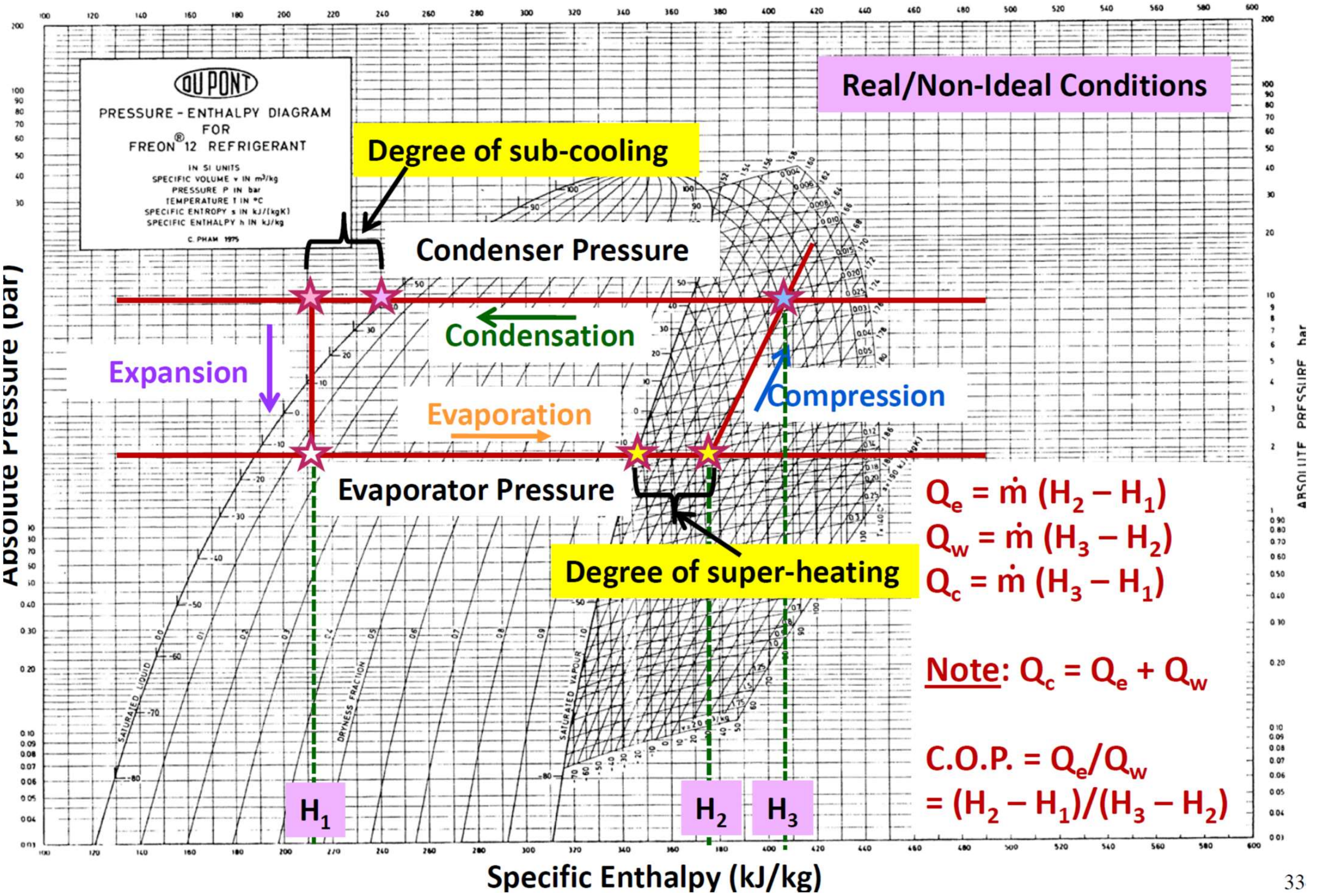
$$(\mathrm{COP}_{\mathrm{REF}}) = \frac{\text{Refrigeration Effect} \ \text{KJ/Kg}}{\text{Work Done} \ \text{KJ/Kg}}$$

$$(\mathrm{COP}_{\mathrm{HP}}) = \frac{\text{Condenser Heat Rejection} \ \text{KJ/Kg}}{\text{Work Done} \ \text{KJ/Kg}}$$

Pressure-Enthalpy Diagram for R-12



Pressure-Enthalpy Diagram for R-12



$Q_e = \dot{m}\,(H_2 - H_1)$

$Q_w = \dot{m}\,(H_3 - H_2)$

$Q_c = \dot{m}\,(H_3 - H_1)$

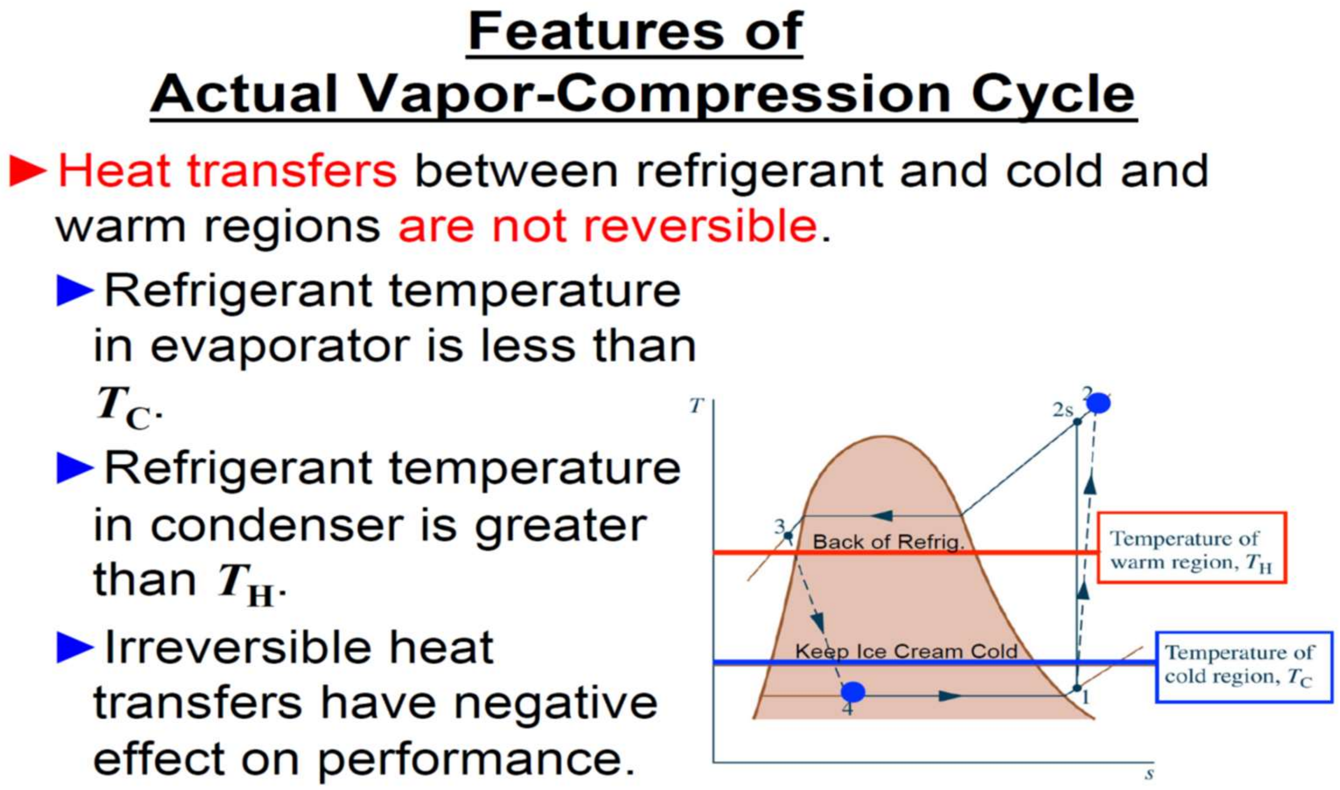
<u>Note</u>: $Q_c = Q_e + Q_w$

C.O.P. $= Q_e/Q_w$

$= (H_2 - H_1)/(H_3 - H_2)$

Actual Vapor-compression Refrigeration Cycle

An actual vapor-compression refrigeration cycle differs from the ideal one in several ways, owing mostly to the irreversibilities that occur in various components, mainly due to fluid friction (causes pressure drops) and heat transfer to or from the surroundings. The COP decreases as a result of irreversibilities.

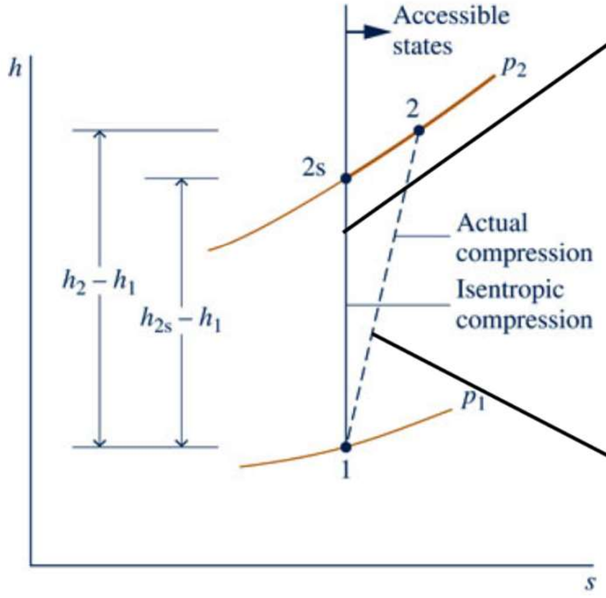


Features of Actual Vapor-Compression Cycle

- Heat transfers between refrigerant and cold and warm regions are not reversible.
  - Refrigerant temperature in evaporator is less than T_C.
  - Refrigerant temperature in condenser is greater than T_H.
  - Irreversible heat transfers have negative effect on performance.

Isentropic Compressor Efficiency

- The isentropic compressor efficiency is the ratio of the minimum theoretical work input to the actual work input, each per unit of mass flowing:



work required in an isentropic compression from compressor inlet state to the exit pressure

$$\eta_c = \frac{(-\dot{W}_{cv}/\dot{m})_s}{(-\dot{W}_{cv}/\dot{m})} = \frac{h_{2s} - h_1}{h_2 - h_1}$$

(Eq. 6.48)

work required in an actual compression from compressor inlet state to exit pressure

Actual Vapor-Compression Cycle

Example: The table provides steady-state operating data for a vapor-compression refrigeration cycle using **R-134a** as the working fluid. For a refrigerant mass flow rate of **0.08 kg/s**, determine the

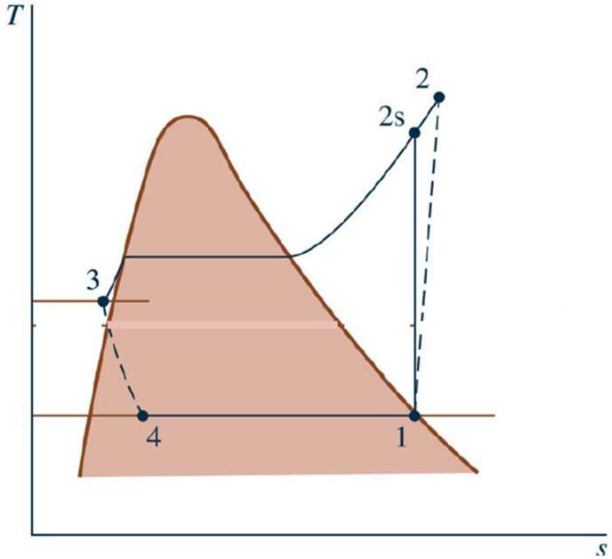
(a) compressor power, in **kW**,

(b) refrigeration capacity, in **tons**,

(c) coefficient of performance,

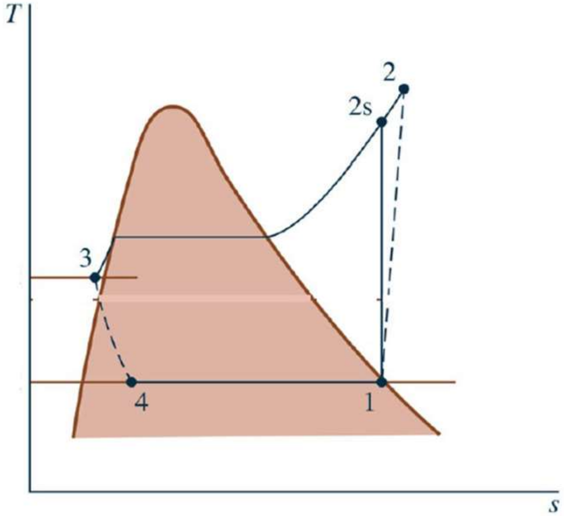
(d) isentropic compressor efficiency.

State	**1**	**2s**	**2**	**3**	**4**
***h* (kJ/kg)**	**241.35**	**272.39**	**280.15**	**91.49**	**91.49**



Actual Vapor-Compression Cycle

State	1	2s	2	3	4
h (kJ/kg)	241.35	272.39	280.15	91.49	91.49



(a) The **compressor power** is

$$\dot{W}_{\mathrm{c}} = \dot{m}(h_2 - h_1)$$

$$\dot{W}_{\mathrm{c}} = \left(0.08\frac{\mathrm{kg}}{\mathrm{s}}\right)(280.15 - 241.35)\frac{\mathrm{kJ}}{\mathrm{kg}}\left|\frac{1\,\mathrm{kW}}{1\,\mathrm{kJ/s}}\right| = \mathbf{3.1\ kW}$$

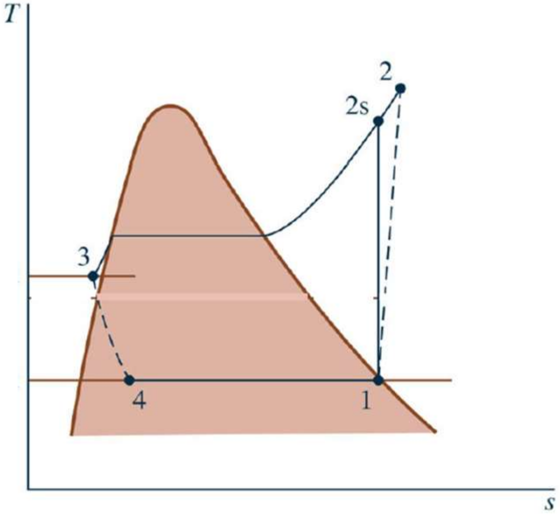
(b) The **refrigeration capacity** is

$$\dot{Q}_{\mathrm{in}} = \dot{m}(h_1 - h_4)$$

$$\dot{Q}_{\mathrm{in}} = \left(0.08\frac{\mathrm{kg}}{\mathrm{s}}\right)(241.35 - 91.49)\frac{\mathrm{kJ}}{\mathrm{kg}}\left|\frac{1\,\mathrm{ton}}{211\,\mathrm{kJ/min}}\right|\left|\frac{60\,\mathrm{s}}{\mathrm{min}}\right| = \mathbf{3.41\ tons}$$

Actual Vapor-Compression Cycle

State	1	2s	2	3	4
h (kJ/kg)	241.35	272.39	280.15	91.49	91.49



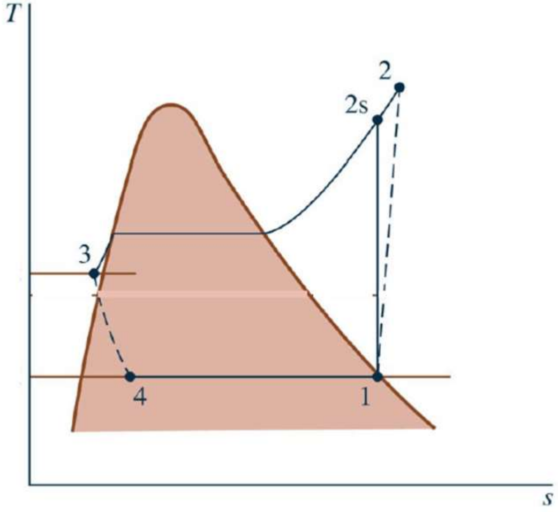
(c) The **coefficient of performance** is

$$\beta = \frac{(h_1 - h_4)}{(h_2 - h_1)}$$

$$\beta = \frac{(241.35 - 91.49)\text{kJ/kg}}{(280.15 - 241.35)\text{kJ/kg}} = \mathbf{3.86}$$

Actual Vapor-Compression Cycle

State	1	2s	2	3	4
h (kJ/kg)	241.35	272.39	280.15	91.49	91.49



(d) The **isentropic compressor efficiency** is

$$\eta_c = \frac{\left(\dot{W}_c / \dot{m}\right)_s}{\dot{W}_c / \dot{m}} = \frac{(h_{2s} - h_1)}{(h_2 - h_1)}$$

$$\eta_c = \frac{(272.39 - 241.35)\text{kJ/kg}}{(280.15 - 241.35)\text{kJ/kg}} = \mathbf{0.8 = 80\%}$$

3. REFRIGERANTS

Selecting Refrigerants

► Refrigerant selection is based on several factors:

- ► Performance: provides adequate cooling capacity cost-effectively.
- ► Safety: avoids hazards (i.e., toxicity).
- ► Environmental impact: minimizes harm to stratospheric ozone layer and reduces negative impact to global climate change.

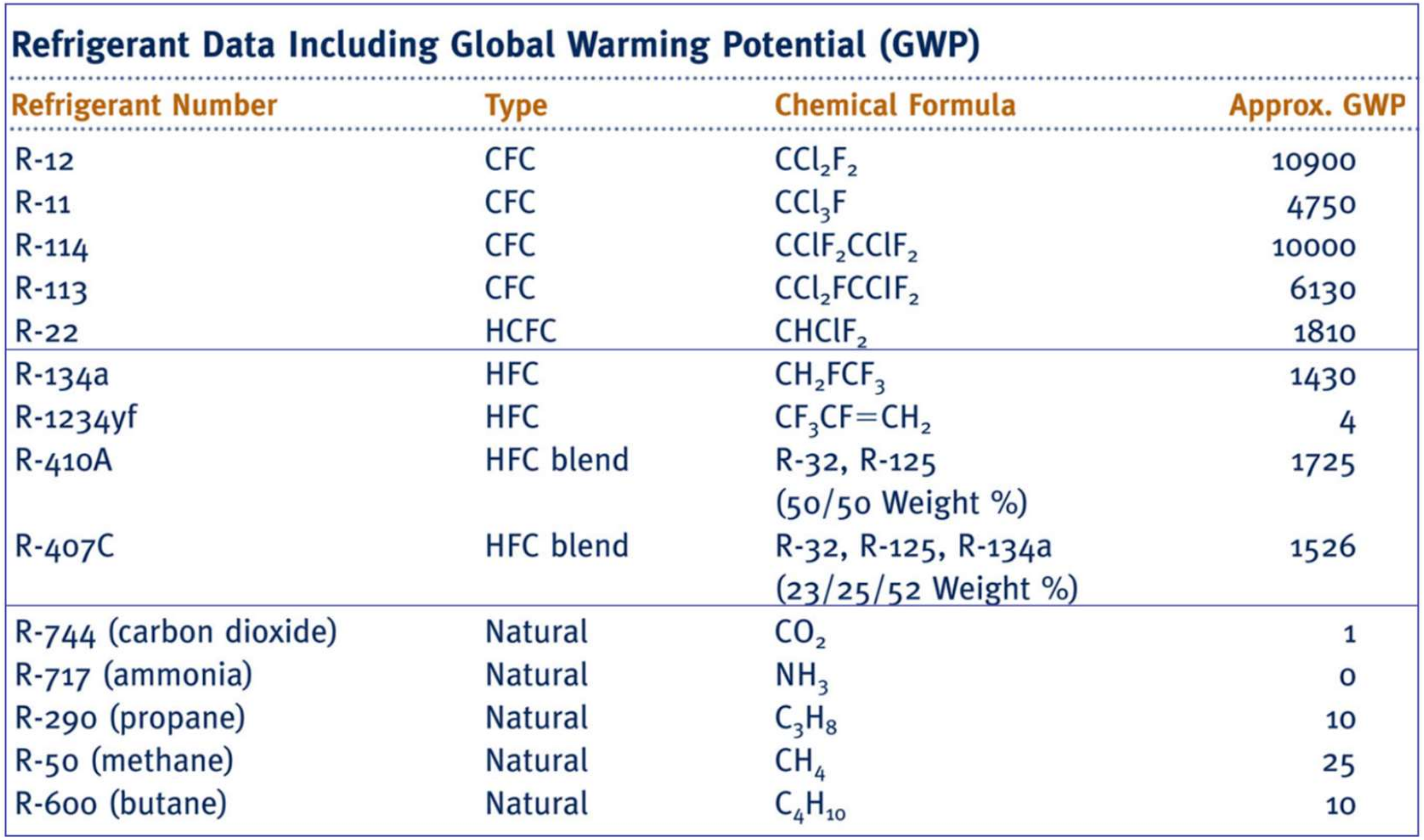
Refrigerant Types and Characteristics

►**Chlorofluorocarbons (CFCs) and Hydrochlorofluorocarbons (HCFCs)** are early synthetic refrigerants each containing chlorine. Because of the adverse effect of chlorine on Earth's stratospheric ozone layer, use of these refrigerants is regulated by international agreement.

►**Hydrofluorocarbons (HFCs) and HFC blends** are chlorine-free refrigerants. Blends combine two or more HFCs. While these chlorine-free refrigerants do not contribute to ozone depletion, with the exception of R-1234yf, they have high GWP levels.

►**Natural refrigerants** are nonsynthetic, naturally occurring substances which serve as refrigerants. These include carbon dioxide, ammonia, and hydrocarbons. These refrigerants feature low GWP values; still, concerns have been raised over the toxicity of NH_3 and the safety of the hydrocarbons.

Refrigerant Types and Characteristics



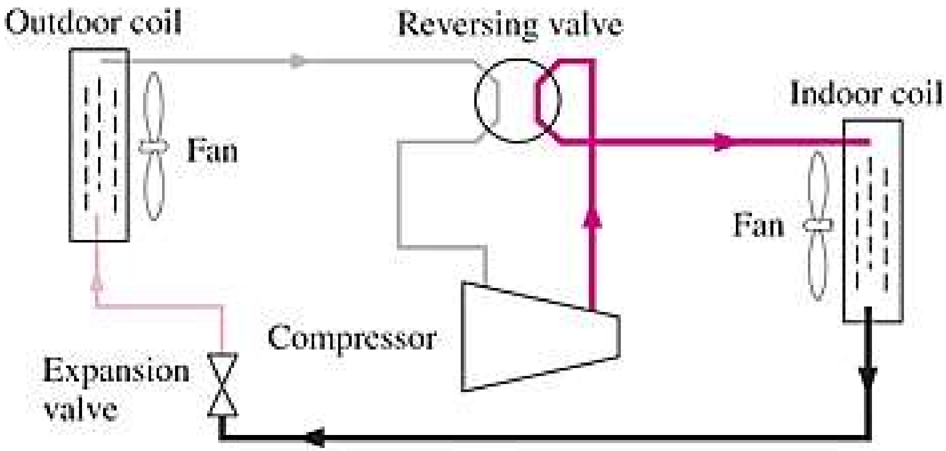
Refrigerant Data Including Global Warming Potential (GWP)

Refrigerant Number	Type	Chemical Formula	Approx. GWP
R-12	CFC	CCl_2F_2	10900
R-11	CFC	CCl_3F	4750
R-114	CFC	$CClF_2CClF_2$	10000
R-113	CFC	CCl_2FCClF_2	6130
R-22	HCFC	$CHClF_2$	1810
R-134a	HFC	CH_2FCF_3	1430
R-1234yf	HFC	$CF_3CF{=}CH_2$	4
R-410A	HFC blend	R-32, R-125 (50/50 Weight %)	1725
R-407C	HFC blend	R-32, R-125, R-134a (23/25/52 Weight %)	1526
R-744 (carbon dioxide)	Natural	CO_2	1
R-717 (ammonia)	Natural	NH_3	0
R-290 (propane)	Natural	C_3H_8	10
R-50 (methane)	Natural	CH_4	25
R-600 (butane)	Natural	C_4H_{10}	10

Global Warming Potential (GWP) is a simplified index that estimates the ***potential future influence on global warming*** associated with different gases when released to the atmosphere.

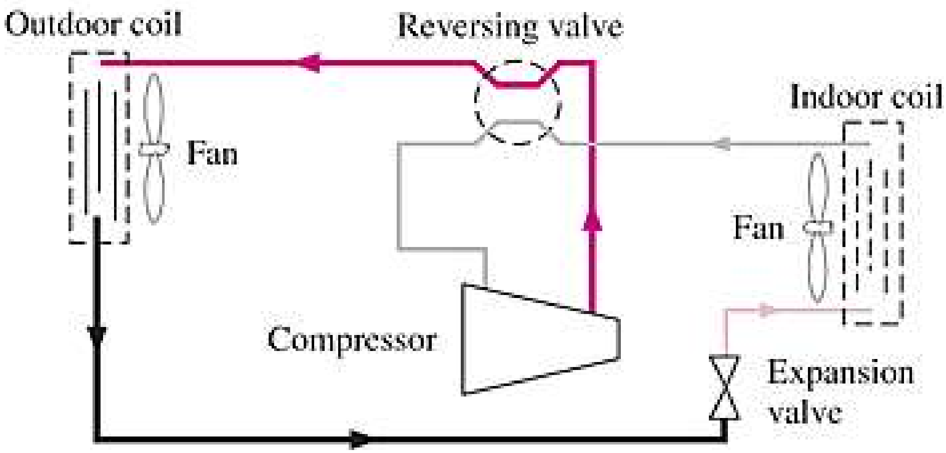
4. HEAT PUMP SYSTEMS

HEAT PUMP OPERATION—HEATING MODE



A heat pump can be used to heat a house in winter and to cool it in summer.

HEAT PUMP OPERATION—COOLING MODE



The most common energy source for heat pumps is atmospheric air (air-to-air systems).

Water-source systems usually use well water and ground-source (geothermal) heat pumps use earth as the energy source. They typically have higher COPs but are more complex and more expensive to install.

Both the capacity and the efficiency of a heat pump fall significantly at low temperatures. Therefore, most air-source heat pumps require a supplementary heating system such as electric resistance heaters or a gas furnace.

Heat pumps are most competitive in areas that have a large cooling load during the cooling season and a relatively small heating load during the heating season. In these areas, the heat pump can meet the entire cooling and heating needs of residential or commercial buildings.

5. INNOVATIVE VAPOR-COMPRESSION REFRIGERATION SYSTEMS

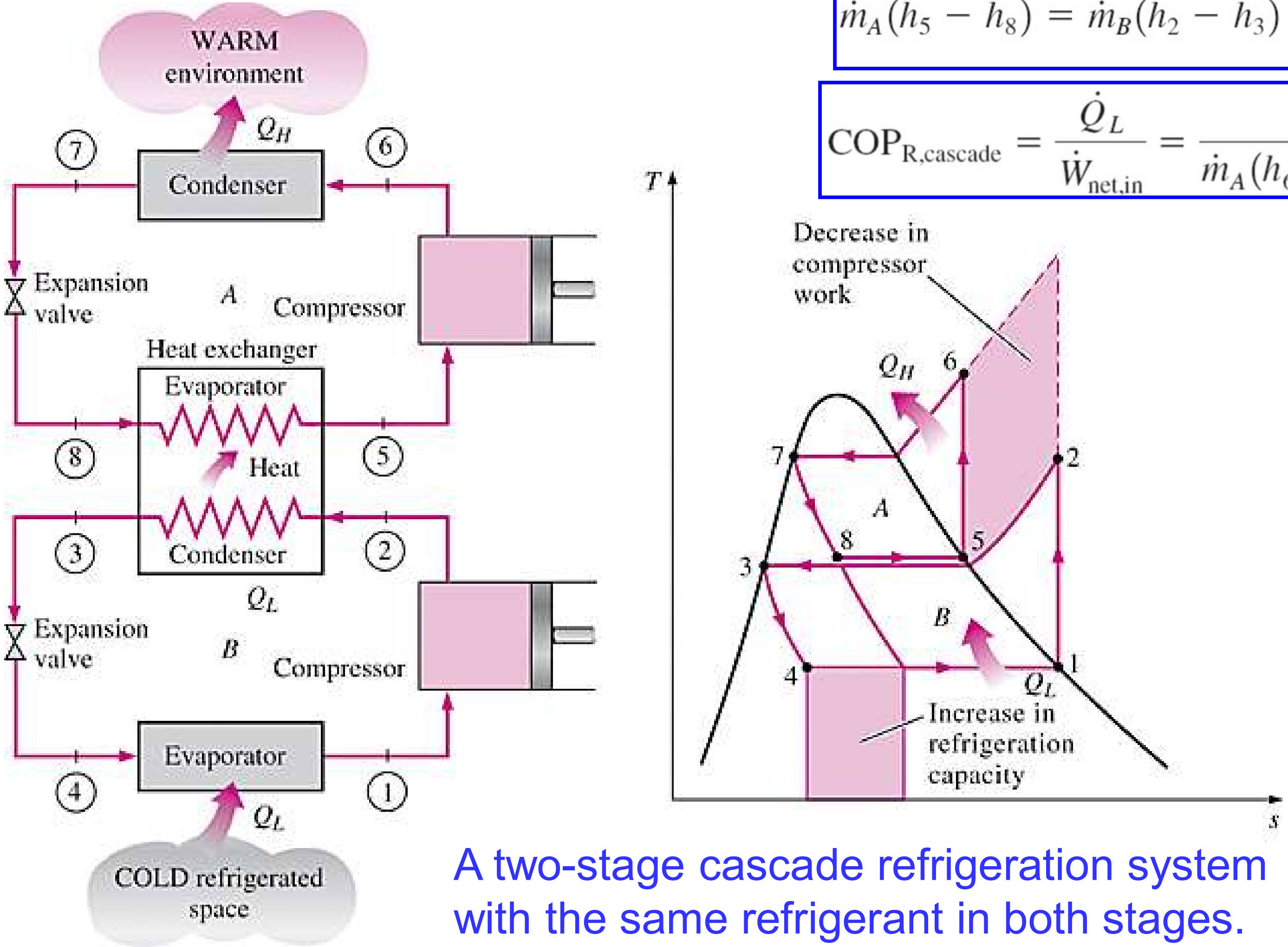
- The simple vapor-compression refrigeration cycle is the most widely used refrigeration cycle, and it is adequate for most refrigeration applications.
- The ordinary vapor-compression refrigeration systems are simple, inexpensive, reliable, and practically maintenance-free.
- However, for large industrial applications *efficiency,* not simplicity, is the major concern.
- Also, for some applications the simple vapor-compression refrigeration cycle is inadequate and needs to be modified.
- For moderately and very low temperature applications some innovative refrigeration systems are used. The following cycles will be discussed:
    - Cascade refrigeration systems
    - Multistage compression refrigeration systems
    - Multipurpose refrigeration systems with a single compressor
    - Liquefaction of gases

Cascade Refrigeration Systems

Some industrial applications require moderately low temperatures, and the temperature range they involve may be too large for a single vapor-compression refrigeration cycle to be practical. The solution is **cascading.**

$$\dot{m}_A(h_5 - h_8) = \dot{m}_B(h_2 - h_3) \longrightarrow \frac{\dot{m}_A}{\dot{m}_B} = \frac{h_2 - h_3}{h_5 - h_8}$$

$$\text{COP}_{\text{R,cascade}} = \frac{\dot{Q}_L}{\dot{W}_{\text{net,in}}} = \frac{\dot{m}_B(h_1 - h_4)}{\dot{m}_A(h_6 - h_5) + \dot{m}_B(h_2 - h_1)}$$



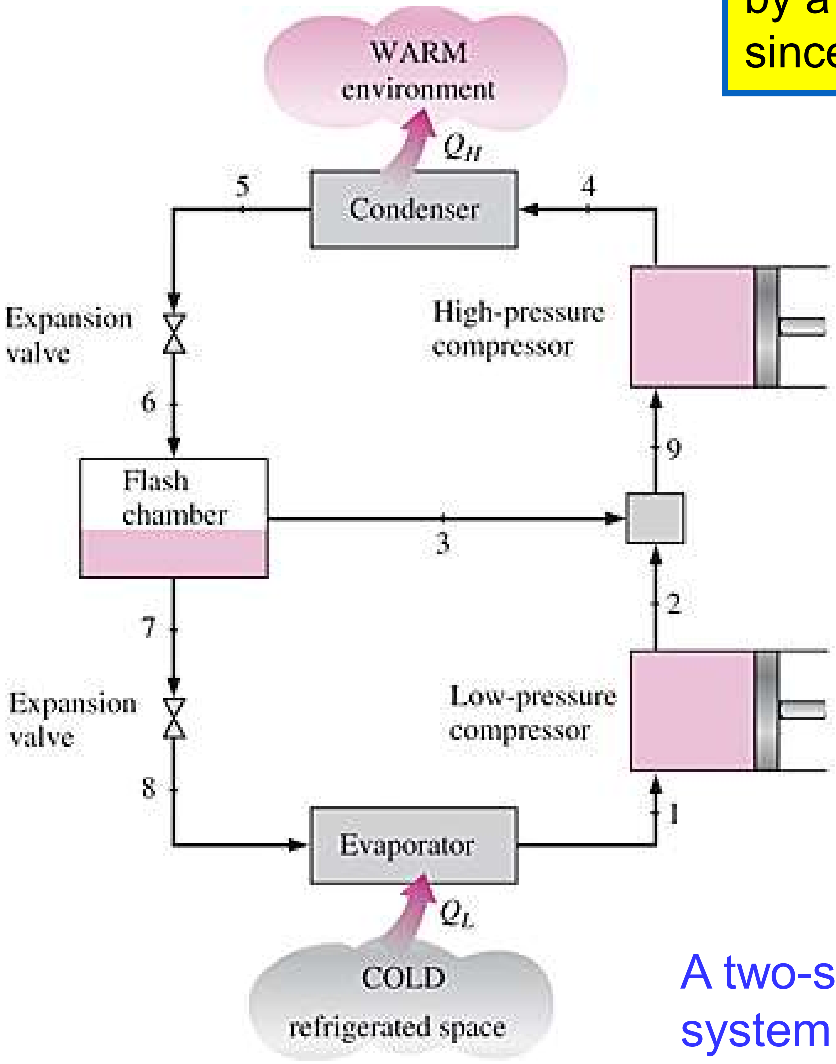
A two-stage cascade refrigeration system with the same refrigerant in both stages.

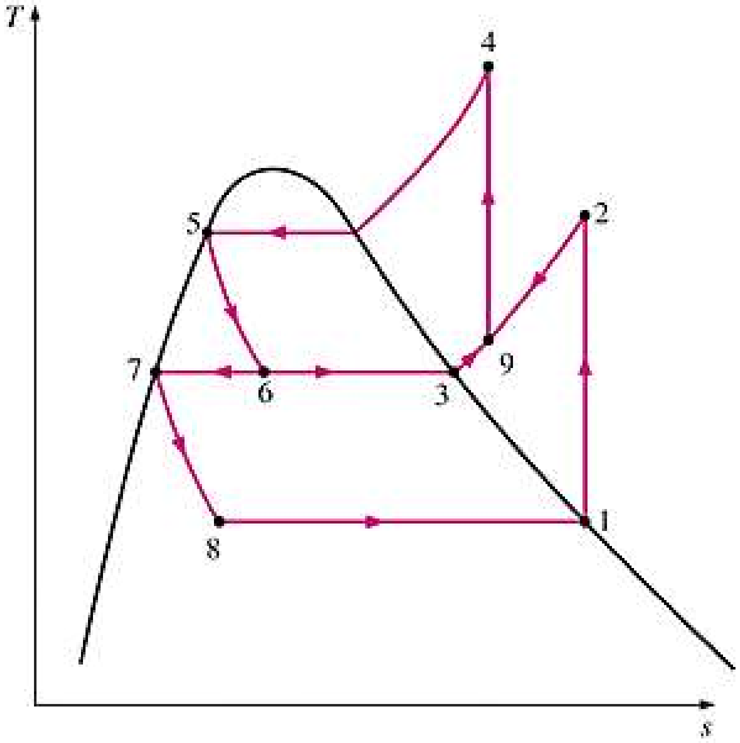
Cascading improves the COP of a refrigeration system.

Some systems use three or four stages of cascading.

Multistage Compression Refrigeration Systems

When the fluid used throughout the cascade refrigeration system is the same, the heat exchanger between the stages can be replaced by a mixing chamber (called a *flash chamber*) since it has better heat transfer characteristics.

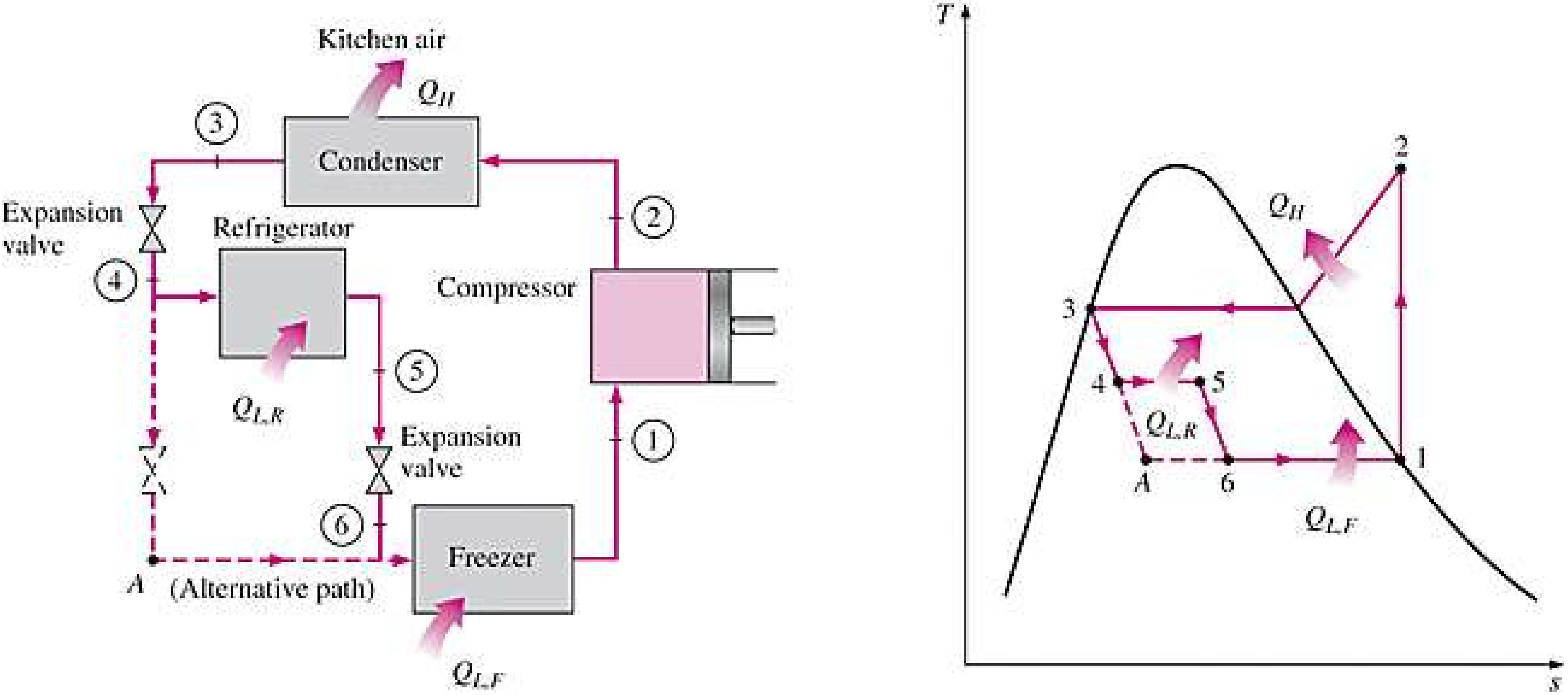




A two-stage compression refrigeration system with a flash chamber.

Multipurpose Refrigeration Systems with a Single Compressor

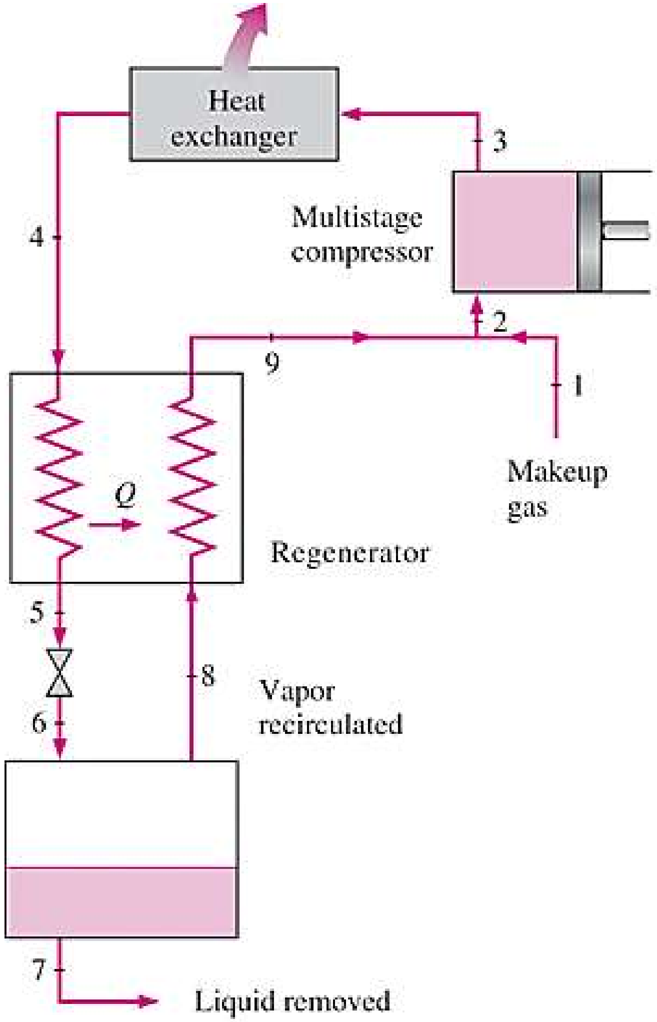
Some applications require refrigeration at more than one temperature. A practical and economical approach is to route all the exit streams from the evaporators to a single compressor and let it handle the compression process for the entire system.



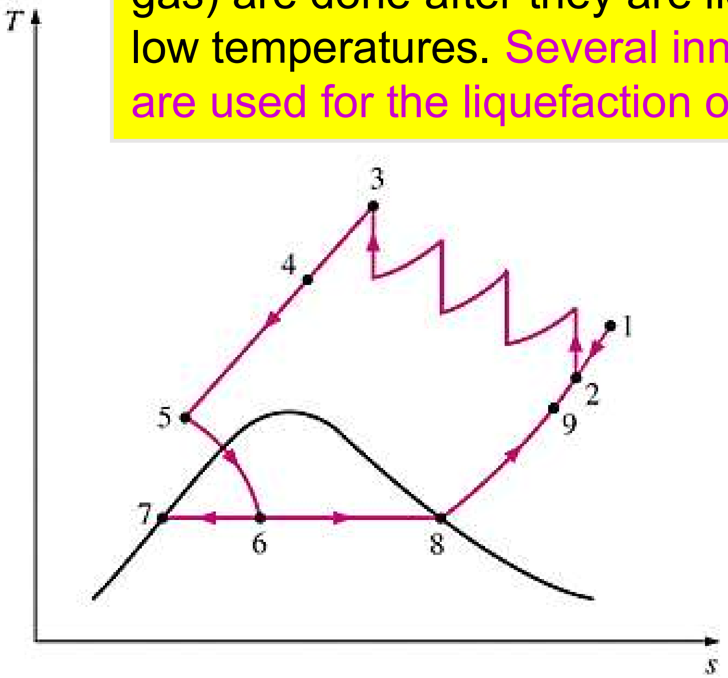
Schematic and *T*-*s* diagram for a refrigerator–freezer unit with one compressor.

Liquefaction of Gases

Many important scientific and engineering processes at cryogenic temperatures (below about 100° C) depend on liquefied gases including the separation of oxygen and nitrogen from air, preparation of liquid propellants for rockets, the study of material properties at low temperatures, and the study of superconductivity.

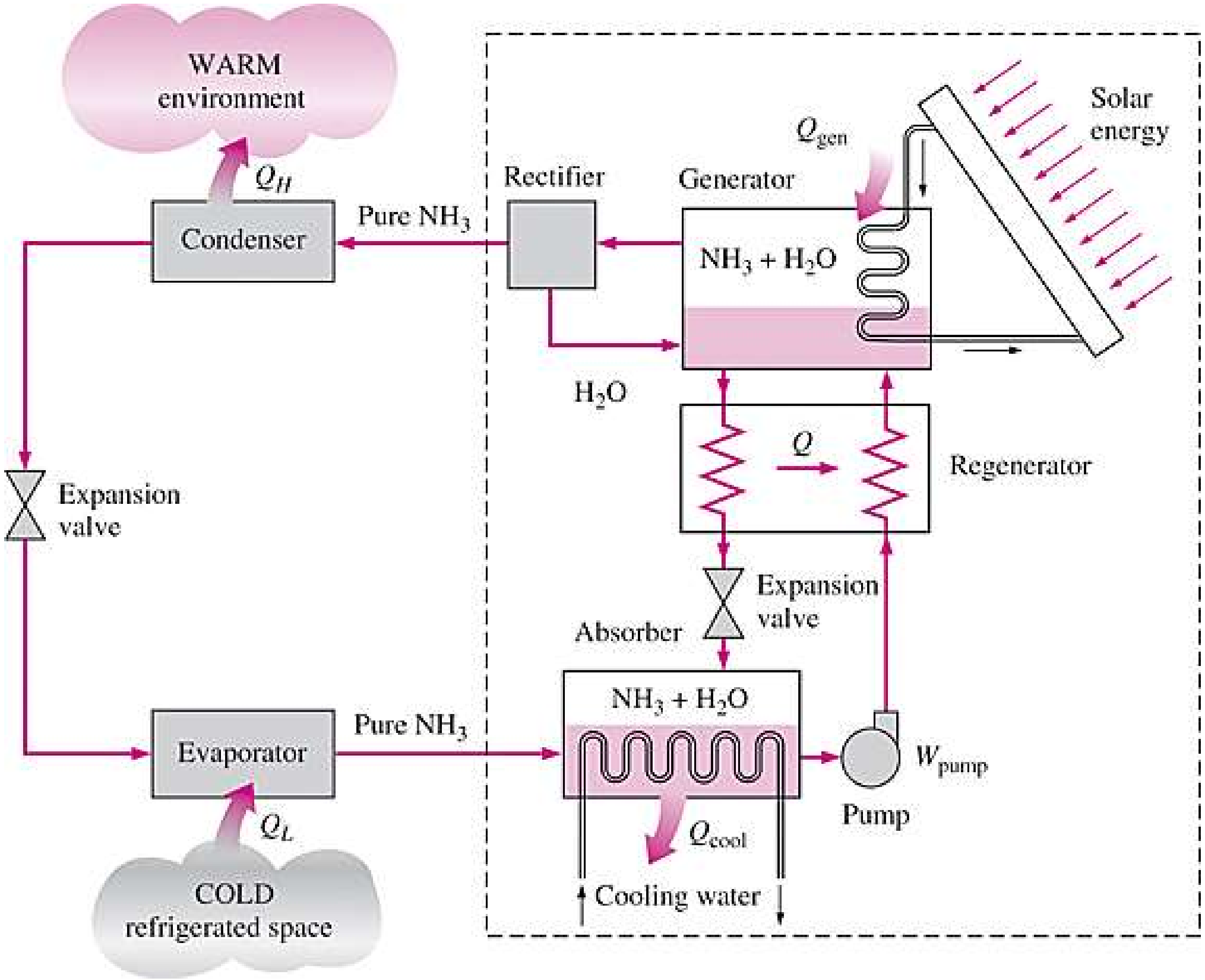


The storage (i.e., hydrogen) and transportation of some gases (i.e., natural gas) are done after they are liquefied at very low temperatures. Several innovative cycles are used for the liquefaction of gases.



Linde-Hampson system for liquefying gases.

5. ABSORPTION REFRIGERATION SYSTEMS

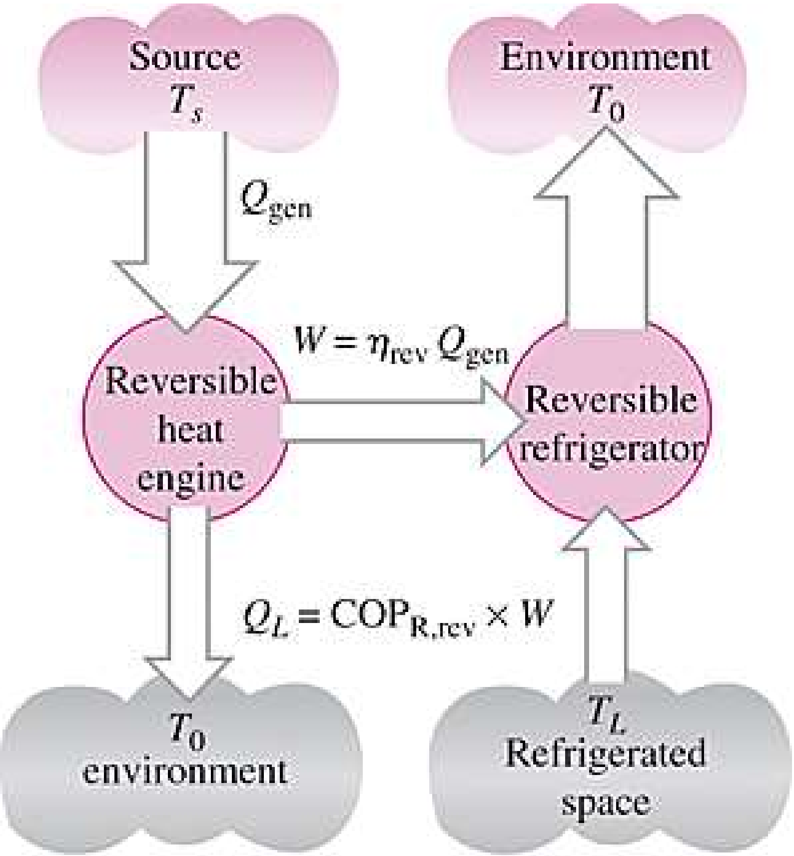


Ammonia absorption refrigeration cycle.

When there is a source of inexpensive thermal energy at a temperature of 100 to 200° C is **absorption refrigeration**.

Some examples include geothermal energy, solar energy, and waste heat from cogeneration or process steam plants, and even natural gas when it is at a relatively low price.

- Absorption refrigeration systems (ARS) involve the absorption of a *refrigerant* by a *transport medium*.
- The most widely used system is the ammonia–water system, where ammonia (NH_3) serves as the refrigerant and water (H_2O) as the transport medium.
- Other systems include water–lithium bromide and water–lithium chloride systems, where water serves as the refrigerant. These systems are limited to applications such as A-C where the minimum temperature is above the freezing point of water.
- Compared with vapor-compression systems, ARS have one major advantage: A liquid is compressed instead of a vapor and as a result the work input is very small (on the order of one percent of the heat supplied to the generator) and often neglected in the cycle analysis.
- ARS are often classified as ***heat-driven systems***.
- ARS are much more expensive than the vapor-compression refrigeration systems. They are more complex and occupy more space, they are much less efficient thus requiring much larger cooling towers to reject the waste heat, and they are more difficult to service since they are less common.
- Therefore, ARS should be considered only when the unit cost of thermal energy is low and is projected to remain low relative to electricity.
- ARS are primarily used in large commercial and industrial installations.



$$\text{COP}_{\text{absorption}} = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_L}{Q_{\text{gen}} + W_{\text{pump,in}}} \cong \frac{Q_L}{Q_{\text{gen}}}$$

The COP of actual absorption refrigeration systems is usually less than 1.

Air-conditioning systems based on absorption refrigeration, called ***absorption chillers***, perform best when the heat source can supply heat at a high temperature with little temperature drop.

$$W = \eta_{\text{rev}}\,Q_{\text{gen}} = \left(1 - \frac{T_0}{T_s}\right) Q_{\text{gen}}$$

$$Q_L = \text{COP}_{\text{R,rev}}\,W = \left(\frac{T_L}{T_0 - T_L}\right) W$$

$$\text{COP}_{\text{rev,absorption}} = \frac{Q_L}{Q_{\text{gen}}} = \left(1 - \frac{T_0}{T_s}\right)\left(\frac{T_L}{T_0 - T_L}\right)$$

Determining the maximum COP of an absorption refrigeration system.

REVIEW QUESTIONS

- 1. Describe Ideal Vapor-Compression Refrigeration Cycle I T-S and P-H digram and define the process
- 2. Draw Actual Vapor-Compression Refrigeration Cycle in P-H diagram
- 3. Describe with aid of sketch vapor absorption refrigeration cycle.
- 4. How do you select the right Refrigerant.
- 5. What is the difference between rRefrigeration and heat pump?
- 6. Define COP for refrigerator and heat pump
- 7. What is cascaded refrigeration cycles and what are the advantages.

ASSIGNMENT

1. Design refrigeration cycles for a cold room in Afdera and Semen Mountain parks Using R132 as refrigerant to be maintained -20 oC and determine the COP for both cases.

   The maximum temperature for 97.5 % probability in Afdera is 45OC and Ras Dashen 20oC. Assume that the condenser temperature can be 5 oC above the ambient temperature and the evaporator temperature shall be 5oC below the freeze temperature.