sustainable design

THE SCIENCE OF SUSTAINABILITY AND GREEN ENGINEERING

Daniel A. Vallero
Chris Brasier

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Preface

The authors share a number of things in common. The two that helped shape this book are our interactive style of teaching and our appreciation for the practical aspects of design and engineering. We are constantly searching for real-life examples to bring to the classroom. Many originate from our practice and laboratory. In our view, the academic environment is enriched by our "day jobs," and our practice is enriched by our contact with the creativity and downright audacity of our students. Design demands a sound beginning followed by lifelong learning.

Duke University is a leader in academic enrichment, including its certificate programs. Certificates are intended to immerse students in numerous perspectives of the physical and social sciences, the humanities, and the professions, including engineering, law, medicine, and business. Both of us have directed certificate programs at Duke: Brasier's Architectural Engineering Program and Vallero's Science, Technology and Human Values Program.

This panoply of ideas has caused us to rethink how we teach and learn. Too often, we have seen sustainability and green design as mere slogans or buzz words. People, including faculty and students, merely join the Spaceship Earth chorus, without much thought as to whether what they are advocating makes scientific sense. Fortunately, in our careers, our clients are not so easily convinced. Thus, we must justify any design, including green and sustainable recommendations, by sound science. That is an undercurrent of this book. In fact, we believe that is one of its distinguishing attributes. We do not want to recommend any aspect of a design to our readers that is not justified by sound engineering and rigorous adherence to scientific principles.

Chapter 1 sets the stage for rethinking the conventional design approach. We then immediately direct our attention in the next few chapters to the underpinning sciences. This was a difficult decision. We thought about wading into the hard sciences gradually. However, we are convinced that the design and engineering community needs a readily available resource for "science-based design," so we approached thermodynamics, motion, chemistry, and biology directly.

We are aware of the risks of abruptly confronting the reader with equations, axioms, formulations, and other challenges wrought by scientific vernacular. The reader's eyes may glaze over from seemingly esoteric subject matter. So, for those readers and teachers who would prefer the more gradual approach to green design, we recommend the following chapter sequence:

Society's Call for Green Design

- Chapter 1
- Chapter 4—Second half
- Chapter 5
- Chapter 6

Scientific Underpinning of Green Design

- Chapter 2
- Chapter 3
- Chapter 4—First half
- Chapter 7

The Future of Green Design

- Chapter 8

For social science and humanities workshops and nonscience courses, the sidebars and discussion boxes from Chapters 2 and 3 could be used in place of the equations and related discussions. Actually, we have found that almost any daily newspaper is teeming with articles that provide teachable moments for green design. Thus, our book can be a resource to validate these accounts and to challenge the students to learn more (e.g., by applying a life-cycle analysis).

Both the art and science of green design are exciting! We hope we have found the balance between them to set the stage for truly sustainable designs.

Acknowledgments

We are indebted to many who have provided insights, inspiration, and support in this project. Our students are a continuous font of ideas and challenges, and we are particularly grateful to our first-year students at Duke. We learned long ago that they are refreshingly skeptical and are not intimidated by the letters that

follow our names. The Pratt School of Engineering has been very supportive of our infusion of green and sustainable content into the curriculum. In particular, we thank Tod Laursen, Henri Gavin, and Ana Barros for believing that green engineering courses would enhance Duke's curriculum. Indeed, they have! Tom Rose, Director of the Duke Smart Home Program, authored the discussion boxes on the Home Depot Smart Home at Duke University, a live-in laboratory dedicated to advancing the science of living smarter.

What we know about sustainable design in large measure comes from the insights and reality pointed out over the decades by our colleagues and clients. We want to note in particular those at the United States Environmental Protection Agency; the United States Departments of Defense, Energy, and Transportation; Environment Canada; Health Canada; Carnegie Mellon University; the University of Texas; Texas A&M University; Arizona State University; the Lawrence Berkeley National Laboratory; the International Society for Exposure Analysis; and the Environmental and Occupational Health Sciences Institute.

Jim Harper of Wiley helped make the book a reality. His persistent confidence in this project began almost as soon as the authors'. His colleagues at Wiley, especially Bob Hilbert, are truly gifted in the ways of publishing. This went beyond the norm to bring our ideas to fruition. They provided sounding boards for what was possible beyond what was acceptable. They went the extra mile on last-minute changes and long, hand-written inserts.

Finally, we thank our spouses. They have always been supportive and understanding, even when it meant unscheduled meetings and postponed activities. They are also our best critics, gently letting us know there "may" be a better way to convey an idea than what we had originally shared with them.

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chapter 1

The Evolution of Design Process

The exact point in time when design professions' embrace of green principles changed from a desirable commodity to a fully integrated design expectation is probably lost in history. The difference between both designer and client expectations now versus the 1990s is striking. Green design transcends mere descriptions of the techniques that may be employed in shaping a more sustainable existence on Earth. It must also incorporate the principles, processes, and cycles of nature in a way that leads to a deeper understanding of what makes a design successful. Ideally, a book in the first decade of the third millennium that addresses green design should form the foundation for exploration and discovery of new and innovative ways to minimize ecological footprints. But it must be even more than avoiding the negative. Now, and from now on, designers must strive for an end product that mutually benefits the client, the public, and the environment.

It is only through creating a better understanding of the natural world that new strategies can emerge to replace the entrenched design mind-sets that have relied on traditional schemes steeped in an exploitation of nature. Designs of much of the past four centuries have assumed an almost inexhaustible supply of resources. We have ignored the basic thermodynamics.

Almost everything we do in some way affects the health of the planet, from showering and brushing our teeth in the morning to well after we are finally tucked in at the end of the day, and the small clock on our nightstand continues to demand energy from the grid. One of the great misconceptions of scientists and nonscientists alike is that environmental consciousness is not dictated by sound science. To the contrary, everything that we do to the environment can be completely explained scientifically. The good news is that by applying the laws of science, we can shape our environment and provide the products demanded by society both predictably and sustainably. That is, strategic use of the principles of physical science informs our designs and engineering decisions.

Such thoughtfulness will moderate or even eliminate the slowly unraveling web of nature that has been accelerating at an alarming rate. Innovators such as Albert Einstein have noted that new and emerging problems demand new approaches and ways of thinking. "The significant problems we face cannot be solved at the same level of thinking we were at when we created them."[1] Our hope is that this book is one of the building blocks of the next stage of green design. We advocate taking proactive steps toward evolving our thinking about solutions to the many complex environmental challenges we face at the beginning of the twenty-first century.

Since the industrial revolution of the nineteenth century, architects and engineers have been key players (culprits?) in the war against nature. Single-minded exploitation and subjugation of nature was the norm during much of the twentieth century and persists as a mainstay of design. Technology has hastened the process. Notably, "man-made weather" (i.e., air conditioning) is now a universal expectation of building design in the West, following the invention of an "apparatus for treating air" patented by Willis Carrier in 1906.[2] It is also entrenched in the desire for conformation of the International Style of Architecture, which spanned much of the twentieth century. Many of us follow the remnants of this style, still seeking one universal building, regardless of climate and place. We take great comfort in our templates. What worked last time surely *must* work again this time.

Actually, green thinking is not new at all. In fact, our new way of thinking resembles an understanding of and respect for nature found in antiquity, as evidenced by the designs of cliff-dwelling native peoples. Reestablishing the link between built form and the environment will require a more complete understanding of the science that underpins successful sustainable design strategies, and incorporating this knowledge as architects and engineers engaged in shaping our world along with the construction community charged with realizing a new vision. In *Cradle to Cradle*, McDonough and Braungart note the challenge of this approach: "For the engineer that has always taken—indeed has been trained his or her entire life to take—a traditional, linear, cradle to grave approach, focusing on one-size-fits-all tools and systems, and who expects to use materials and chemicals and energy as he or she has always done, the shift to new models and more diverse input can be unsettling."[3]

A more complete understanding of the first principles of science and a reexamination of the "normal" process of conception and delivery in the design and construction communities puts the green designer in a position of strength. These principles provide the knowledge needed to challenge those who choose to "green wash" a product by presenting only a portion of the entire story of a product's environmental impact. For example, a product may indeed be "phosphate free," which means that it does not contain one of the nutrients that can lead to eutrophication of surface waters. However, this does not translate directly into an ecologically friendly product, especially if its life cycle includes steps that are harmful, such as destruction of habitat in material extraction, use and release of toxic materials in manufacturing, and persistent chemical by-products that remain hazardous in storage, treatment, and disposal. For example, simply replacing the solvent with a water-based solution is often desirable, and can rightly be called "solvent free,"[4] but under certain scenarios may make a product more dangerous, since many toxic substances, such as certain heavy metal compounds, are highly soluble in water (i.e., hydrophilic). Thus, our "improved" process has actually made it easier for any heavy metals contained in the solution to enter the ecosystem and possibly lead to human exposures.

The *law of unintended consequences* is ever ready to raise its ugly head in design. There are numerous examples of building design solutions touted as sustainable that fail to recognize and respond to the specifics of local climate. A building project that has applied sustainable principles with the mind-set that these principles are "universal" solutions will produce less than optimal results, if not total failure. For example, a wind system is renewable but is not necessarily efficient. Incorporating wind turbines without first understanding local climate and the physics of wind-generated energy could lead to poor design solutions by placing turbines in an area that does not generate sufficient wind speeds throughout the year.

The idea of a more "holistic" approach is required to arrive at complete, sustainable design strategies. The notion of life cycle in the design and construction community has too often been confined to a cost–benefit economic model of demonstrating the return on investment that can be expected over the life of a building. Although this approach to applying a financial model demonstrates the return on investment of sound design choices, the concept must also be applied beyond a comparison of the initial investment as a fraction of the total cost of operating and maintaining a building or system to an expanded definition beyond pure economics. For example, design decisions on how we shape our environment also include less tangible impacts on the individual, society, and ecology that may not fit neatly on a data spreadsheet.

PROCESS: LINEAR AND CYCLICAL DESIGN

The critical path from building conception to completion has changed very little over the thousands of years since humans began to shape the environment to create shelter from the elements. The first builders harvested locally available materials, and assemblies grew from trial and error and from observation of the structures found in nature. Trial and error created the feedback loop that guided the technical development of these structures. Marcus Vitruvius Pollio is believed to have authored *De Architectura* (*On Architecture*), written in the first century B.C. *De Architectura* provided one of the first sources of guidance for building, containing 10 chapters, or 10 "books." Codifying existing practice on topics ranging from building materials to proportional relationships based on the human body, the text served for centuries as an influential reference. Vitruvius wrote of architecture as being an imitation of nature, and a central tenant of his writing was the suggestion that a structure must contain three essential qualities: "*firmitas*, *utilitas,* and *venustas*." *Firmitas* is translated from Latin as firmness or strength, *utilitas* suggests commodity or usefulness, and *venustas* is a quality of delight or beauty. These remain as core design criteria. Engineers emphasize the first two, and architects give much attention to the second two.

Leonardo da Vinci, Michelangelo, Filippo Brunelleschi, and other key design figures of the Renaissance did not distinguish boundaries between the roles of artist, architect, and engineer (see Fig. 1.1). The Renaissance master builder represents the next step in the evolution of rationalizing the process with the introduction of science and engineering principles. The emergence of architectural treatises, increased physical challenges of larger spans, and a desire for an increasingly rich aesthetic expression all contributed to the growing complexity in navigating this pathway from conception to completion. The master builder of the Renaissance played the roles of architect, engineer, material scientist, and builder, simultaneously serving as the source of inspiration, technical resolution, and delivery. Florentine architect Brunelleschi (1377–1446) was a seminal figure

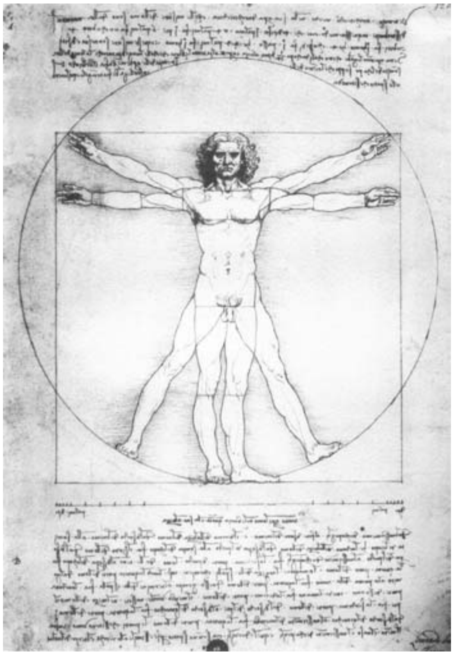


Figure 1.1 *Vitruvian Man*, illustrated by Leonardo da Vinci.

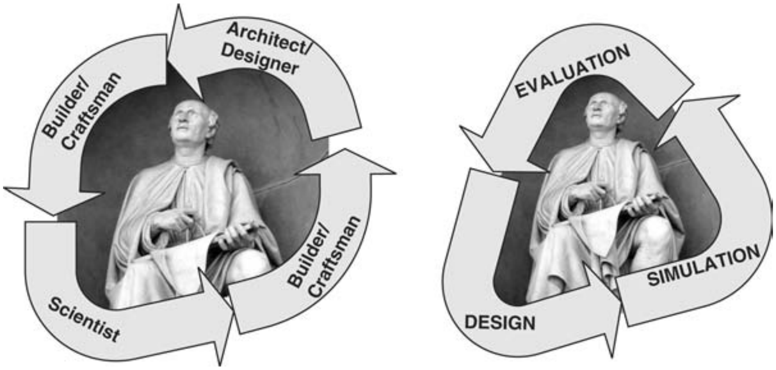


Figure 1.2 Filippo Brunelleschi as master builder.

in the Renaissance period who studied science and mathematics (see Fig. 1.2). He began as a painter and sculptor, and then became a master goldsmith, with most of his success in acquiring important architectural commissions attributed to his technical genius.

It was not until the industrial revolution that boundaries between professions began to become distinct, opening a path toward specialization. The twentieth century witnessed the acceleration of this migration toward specialization, as building systems became more complex and the number and diversity of building typologies grew. The industrial revolution brought the rise of transportation and manufacturing infrastructure, providing the ability to fabricate components off-site and assemble on-site. This increasing complexity begins a transition away from the model of master builder along with the emergence of discrete professional disciplines, and eventually, further fragmentation within these disciplines as the roles of design and technical expertise no longer reside in any one individual.

The single defining and unchanging characteristic of the building professions remains the act of designing. *Merriam-Webster Collegiate Dictionary* defines *design* as "to create, fashion, execute, or construct according to plan" and "to conceive and plan out in the mind." Research, analysis, optimization, constraint identification, prototyping, and many other facets of the design process remain common to all design professions. Depending on the design specialty or disciplines, the scientific and aesthetic principles are applied in differing measures to achieve the core objective of problem solving.

The actual view of the process of design, however, varies substantially both within the professions and between design disciplines. Some view the process as purely direct, sequential, and linear, following a prescribed set of activities that will lead to a final solution. This stepwise approach is often referred to as the *waterfall model*, drawing on the analogy of water flowing continuously through the phases of design. This approach has value, especially when the number of variables are manageable and a limited universe of possible solutions are well behaved and predictable. An example of this approach would include a “prototype” design that is simply being adapted to a new condition. This process is often the most direct, conventional, and least costly when “first cost” is a primary consideration. For example, a reduction in the time required for design and delivery can mitigate the impact of price escalation due to inflation and other market variables. Most projects are planned around schedules that appear to be linear, but the actual activity within each phase tends to be somewhat nonlinear (e.g., feedback loops are needed when unexpected events occur).

Building Design Process

The process of design and delivery of buildings in particular, from conception to completion, has generally followed a linear or stepwise model in which distinct phases guide the design from definition of need or problem statement, followed by drawings through technical evolution, construction, and final completion. As illustrated in Figure 1.3, the path from project conception to completion follows a stepped progression with discrete phases for each stage of the project’s development. Much of the work and many of the insights are provided by the designer well into the process. Some technical input is sought early, but it is very limited. The builder typically does not provide input until midway through the process, but at the end is almost exclusively responsible for the project. This “hand-offs” approach can lead to miscommunication and the lack of opportunity to leverage different perspectives. Even if the builder has good, green ideas from experience, the process may be too far along to incorporate them without substantial costs and need to retrofit.

The progression of the stepwise process from idea to realization is a sequence of events and involvement of specialized expertise. This process can be thought of

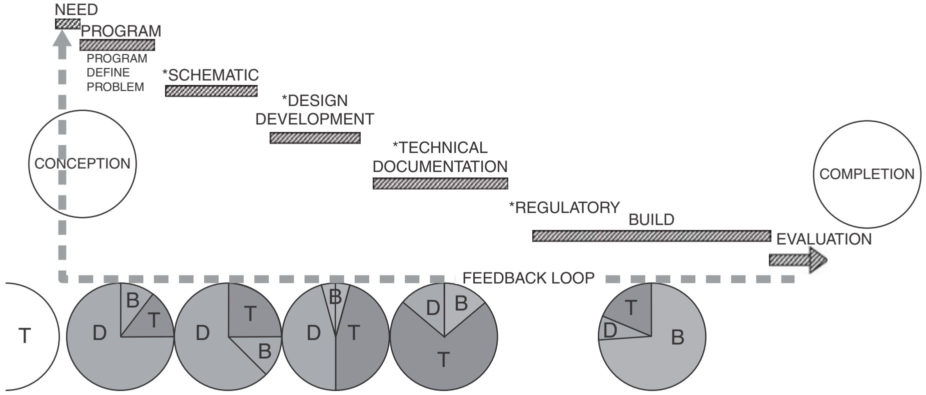


Figure 1.3 Rational, linear design model.

Note: D, design expertise; T, technical expertise; B, building expertise; *= review cycle.

as analogous to the conceiving of a new living organism. The process begins with the necessary definitions of the essential systems to support this new form of life. Next, performance characteristics are defined in precise detail to communicate assembly (embryonic growth). Finally, the concept is realized (born) by translating this vision from two-dimensional constructs into three-dimensional reality. Let us consider each step in a bit more detail, applying the analogy of the living organism to the design process.

Program or Problem Statement

Linear progression of the process would logically begin with a clear definition of the problem to be solved. In this case it is essential to pose questions of our client to determine in sufficient detail the goals for this new living organism, organizational form and systems, and how these will interact and influence each other in the functioning of the whole. It would also be helpful to understand and characterize the environment in which this organism will reside and the potential for symbiotic relationships within this ecosystem.

Skeletal Form or Schematic

Once the data are collected and understood, the logical next step in the design process would be to synthesize alternatives for weaving these forms together to create a skeletal framework or *schematic* for the new organism. This frame provides the basic support structure and places the forms identified in the first step in the most appropriate relationship with one another, seeking optimization of the design to meet the original goals and objectives most efficiently. At the end of this step, as a measure of design success, the original program or problem statement would be consulted and would serve as a checklist.

Systems Development

With the skeletal frame in place, the design proceeds forward. It moves in a linear fashion to the next rational step, of developing this design concept to incorporate the internal systems required to nourish the organism by transporting air and water, removing waste, and designing a central nervous system that provides the means for individual systems to communicate with one another. The heating, ventilation, air-conditioning, plumbing, and electrical systems for our organism are put in place. Our quality control/quality assurance measures at this point require that we confirm that we indeed have accounted for and incorporated all of the required systems and that they all fit within the skeletal frame developed in the schematics phase.

Technical Detailing and Documentation/Implementation

In the traditional linear model, the focus of the design team shifts from design conception and development to implementation. This transition in focus to the production of technical documents required to communicate the assembly of the design proposal coincides with a dramatic shift away from further synthesis and innovation. Computer-aided design and drafting (CADD), although a relatively new technology, has resulted in dramatic improvements in efficiency but has remained anchored in the processes and methods of the past. While design and drafting are given equal importance in the naming of the tool, the first several generations of this tool's development provided essentially an electronic pencil for drafting, with great new features representing the integration of a number of previously separate and singularly purposed tools: scales for measuring; line and arc function commands replacing T-squares, parallel bars, and compass; and the delete key rendering the eraser obsolete and eradicating all past sins committed in ink.

A TRANSITIONAL MODEL

A linear model of the type we have described, which has remained relatively unchanged for decades, is now beginning to experience significant evolution. The means for ensuring sustainability has been achieved using accountability point systems, such those in the Leadership in Energy and Environmental Design (LEED), BRE Environmental Assessment Method (BREEAM), and Green Globes. Such documentation and recognition of "greenness" has emerged to encourage design and construction professionals to create projects with an eye toward environmental quality. They have often focused on uncovering options that will mitigate a proposed project's environmental impacts. As such, these systems have profoundly changed the design process by moving up the technical input to the earlier phases of a project's development.

In addition to "greening" proposals, designs now undergo a series of integration steps, which have been articulated by Mendler et al.[5]:

1. Project description
2. Team building

3. Education and goal setting
4. Site evaluation
5. Baseline analysis
6. Design concept
7. Design optimization
8. Documentation and specifications
9. Building and construction
10. Post occupancy

Note that like the stepwise model, this model for the most part does one thing at a time. However, each step includes feedback to the preceding steps (see Figure 1.4). The design concept does not show up until the sixth step and is followed immediately by a comparison of design options. A key difference, however, is the extent of integration of goals into the design process. In fact, Mendler et al. identify global goals that must be part of a green design[6]:

- Waste nothing (a "less is more" approach; reuse, avoiding specification of scarce materials).
- Adapt to the place (indigenous strategies; diversity, form fit to function).
- Use "free" resources (renewable energy, renewable materials, locally abundant resources).

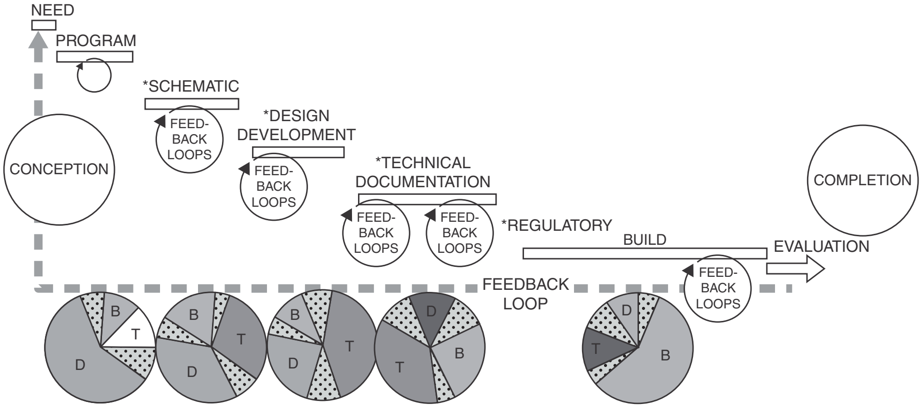


Figure 1.4 Transitional green design model.

Note: D, design expertise; T, technical expertise; B, building expertise; * = review cycle.

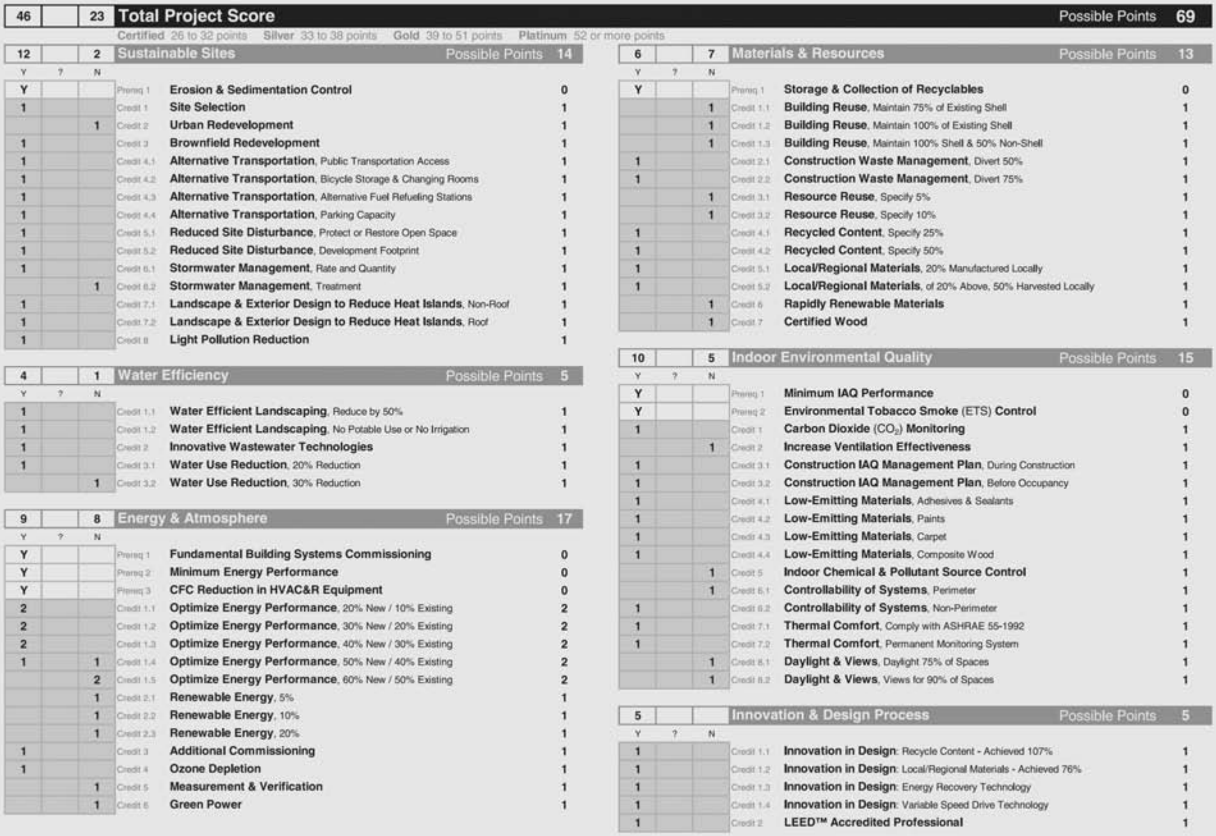
- Optimize rather than maximize (synergies, less reliance on active, mechanical systems).
- Create a livable environment (protect sensitive ecosystems, actively restore damaged habitats, look for pedestrian-friendly and mixed-use design options; avoid toxic materials).

The difference between the stepwise and transitional models is that the former is based on monetary costs, scheduling constraints, and quality; whereas the latter expands to integrate human health, safety, and comfort as well as ecological considerations. The transitional model still pays close attention to the stepwise model's three attributes. In fact, the transitional model requires that even more scrutiny be given to costs, scheduling, and quality, so every step is reviewed in light of the preceding and subsequent steps. The dynamic nature of the model means that more variables are introduced with each step.

The LEED Green Building Rating System was conceived and implemented by the United States Green Building Council (USGBC) to define and measure the sustainability of "green buildings." The USGBC, created in 1993, formed a diverse committee representing expertise in architecture, engineering, real estate, environment, and law focused on the creation of a benchmark for measuring building performance. According to the council, "This cross section of people added a richness and depth to the process and to the ultimate product."[7] Since the introduction of version 2.0 in March 2000, the LEED rating system has begun to transform building design and construction. One of the important by-products of the introduction of this system framework is the increased collaboration between design and construction professionals united by common tools, principles, and the desire to achieve high-performance buildings (see Fig. 1.4). Benefits of the program now extend well beyond the building community, as both the public and private sectors recognize the benefits of sustainable design and now in many cases require the incorporation of these design principles, providing direct and indirect financial incentives and recognition. Another ancillary benefit of the rating system is that it has created markets for green materials. For example, points are given for reusing building materials, such as old ceiling tiles, which had previously found their way to landfills.

Sidebar: Applying the Synthovation/Regenerative Model: Green Buildings

The U.S. Green Building Council has established the Leadership in Energy and Environmental Design (LEED) rating system, which distinguishes "green buildings." The greater the point total, the more sustainable the project. The rating system encourages design and construction practices that reduce the negative impact of buildings. Most of the points are gained using existing, proven technologies. Projects are evaluated according to five separate categories: sustainable site planning, the safeguarding of water and water efficiency, energy efficiency and renewable energy, conservation of materials and resources, and indoor environmental quality. Applicants can earn points in 69 subcategories. An example of a scorecard is shown in Figure S.1.1. The U.S. Environmental Protection Agency (EPA) submitted this card for its Science and Technology Center in Kansas City, Kansas, hoping to earn a gold-level certification. LEED has four certification levels: LEED certified, 26 to 32 points; silver level, 33 to 38 points; gold level, 39 to 51 points; and platinum level, 52 to 69 points.



46		23	**Total Project Score**	Possible Points	69

Certified 26 to 32 points **Silver** 33 to 38 points **Gold** 39 to 51 points **Platinum** 52 or more points

Y	?	N			
12		2	**Sustainable Sites**	Possible Points	14
Y			Prereq 1	**Erosion & Sedimentation Control**	0
1			Credit 1	**Site Selection**	1
		1	Credit 2	**Urban Redevelopment**	1
1			Credit 3	**Brownfield Redevelopment**	1
1			Credit 4.1	**Alternative Transportation**, Public Transportation Access	1
1			Credit 4.2	**Alternative Transportation**, Bicycle Storage & Changing Rooms	1
1			Credit 4.3	**Alternative Transportation**, Alternative Fuel Refueling Stations	1
1			Credit 4.4	**Alternative Transportation**, Parking Capacity	1
1			Credit 5.1	**Reduced Site Disturbance**, Protect or Restore Open Space	1
1			Credit 5.2	**Reduced Site Disturbance**, Development Footprint	1
1			Credit 6.1	**Stormwater Management**, Rate and Quantity	1
		1	Credit 6.2	**Stormwater Management**, Treatment	1
1			Credit 7.1	**Landscape & Exterior Design to Reduce Heat Islands**, Non-Roof	1
1			Credit 7.2	**Landscape & Exterior Design to Reduce Heat Islands**, Roof	1
1			Credit 8	**Light Pollution Reduction**	1

Y	?	N			
4		1	**Water Efficiency**	Possible Points	5
1			Credit 1.1	**Water Efficient Landscaping**, Reduce by 50%	1
1			Credit 1.2	**Water Efficient Landscaping**, No Potable Use or No Irrigation	1
1			Credit 2	**Innovative Wastewater Technologies**	1
1			Credit 3.1	**Water Use Reduction**, 20% Reduction	1
		1	Credit 3.2	**Water Use Reduction**, 30% Reduction	1

Y	?	N			
9		8	**Energy & Atmosphere**	Possible Points	17
Y			Prereq 1	**Fundamental Building Systems Commissioning**	0
Y			Prereq 2	**Minimum Energy Performance**	0
Y			Prereq 3	**CFC Reduction in HVAC&R Equipment**	0
2			Credit 1.1	**Optimize Energy Performance**, 20% New / 10% Existing	2
2			Credit 1.2	**Optimize Energy Performance**, 30% New / 20% Existing	2
2			Credit 1.3	**Optimize Energy Performance**, 40% New / 30% Existing	2
1		1	Credit 1.4	**Optimize Energy Performance**, 50% New / 40% Existing	2
		2	Credit 1.5	**Optimize Energy Performance**, 60% New / 50% Existing	2
		1	Credit 2.1	**Renewable Energy**, 5%	1
		1	Credit 2.2	**Renewable Energy**, 10%	1
		1	Credit 2.3	**Renewable Energy**, 20%	1
1			Credit 3	**Additional Commissioning**	1
1			Credit 4	**Ozone Depletion**	1
		1	Credit 5	**Measurement & Verification**	1
		1	Credit 6	**Green Power**	1

Y	?	N			
6		7	**Materials & Resources**	Possible Points	13
Y			Prereq 1	**Storage & Collection of Recyclables**	0
		1	Credit 1.1	**Building Reuse**, Maintain 75% of Existing Shell	1
		1	Credit 1.2	**Building Reuse**, Maintain 100% of Existing Shell	1
		1	Credit 1.3	**Building Reuse**, Maintain 100% Shell & 50% Non-Shell	1
1			Credit 2.1	**Construction Waste Management**, Divert 50%	1
1			Credit 2.2	**Construction Waste Management**, Divert 75%	1
		1	Credit 3.1	**Resource Reuse**, Specify 5%	1
		1	Credit 3.2	**Resource Reuse**, Specify 10%	1
1			Credit 4.1	**Recycled Content**, Specify 25%	1
1			Credit 4.2	**Recycled Content**, Specify 50%	1
1			Credit 5.1	**Local/Regional Materials**, 20% Manufactured Locally	1
1			Credit 5.2	**Local/Regional Materials**, of 20% Above, 50% Harvested Locally	1
		1	Credit 6	**Rapidly Renewable Materials**	1
		1	Credit 7	**Certified Wood**	1

Y	?	N			
10		5	**Indoor Environmental Quality**	Possible Points	15
Y			Prereq 1	**Minimum IAQ Performance**	0
Y			Prereq 2	**Environmental Tobacco Smoke** (ETS) **Control**	0
1			Credit 1	**Carbon Dioxide** (CO_2) **Monitoring**	1
		1	Credit 2	**Increase Ventilation Effectiveness**	1
1			Credit 3.1	**Construction IAQ Management Plan**, During Construction	1
1			Credit 3.2	**Construction IAQ Management Plan**, Before Occupancy	1
1			Credit 4.1	**Low-Emitting Materials**, Adhesives & Sealants	1
1			Credit 4.2	**Low-Emitting Materials**, Paints	1
1			Credit 4.3	**Low-Emitting Materials**, Carpet	1
1			Credit 4.4	**Low-Emitting Materials**, Composite Wood	1
		1	Credit 5	**Indoor Chemical & Pollutant Source Control**	1
		1	Credit 6.1	**Controllability of Systems**, Perimeter	1
1			Credit 6.2	**Controllability of Systems**, Non-Perimeter	1
1			Credit 7.1	**Thermal Comfort**, Comply with ASHRAE 55-1992	1
1			Credit 7.2	**Thermal Comfort**, Permanent Monitoring System	1
		1	Credit 8.1	**Daylight & Views**, Daylight 75% of Spaces	1
		1	Credit 8.2	**Daylight & Views**, Views for 90% of Spaces	1

Y	?	N			
5			**Innovation & Design Process**	Possible Points	5
1			Credit 1.1	**Innovation in Design**: Recycle Content - Achieved 107%	1
1			Credit 1.2	**Innovation in Design**: Local/Regional Materials - Achieved 76%	1
1			Credit 1.3	**Innovation in Design**: Energy Recovery Technology	1
1			Credit 1.4	**Innovation in Design**: Variable Speed Drive Technology	1
1			Credit 2	**LEED™ Accredited Professional**	1

Figure S.1.1 LEED scorecard submitted for the Science and Technology Center in Kansas City, Kansas.

From U.S. Environmental Protection Agency, "EPA's green future for laboratories: a case study of the Kansas City Science and Technology Center energy" EPA-200-F03-001, U.S. EPA, Washington, DC, 2003.

Laboratories present a particular design challenge. For example, air exchanges are needed to maintain air quality, especially when a laboratory contains hazardous chemicals. Most laboratories need to maintain positive pressure toward fume hoods, which pull air out of the lab space and vent it outdoors. This means that warmed and cooled air also escapes. Thus, safety and green operations can be competing values. However, it does point the way to creativity and innovation. For example, how might heat-exchange systems be used to optimize safety *and* sustainable design?

More information is available at www.usgbc.org/LEED/LEED_main.asp.

THE HOME DEPOT SMART HOME AT DUKE UNIVERSITY

The Home Depot Smart Home at Duke University is a live-in laboratory dedicated to advancing the science of living smarter.

Green Roof

A green roof (also known as a vegetated roof) is an area of roof surface that is covered with living plant matter. In the case of the Home Depot Smart Home at Duke University, the green roof is populated with succulents that are low maintenance and drought resistant. Benefits of green roofs include:

- Preventing heat gain (also known as the urban heat island effect)
- Evaporation creates a cooling effect on the building
- Prefiltering rain water for later use
- Buffering rain water to prevent rapid site run-off
- Pleasing aesthetics
- Increasing the roof lifetime

Water Efficiency

The irrigation system for the Home Depot Smart Home at Duke University uses 100% captured rainwater. This guarantees that no public water will ever be used to water vegetation on the Home Depot Smart Home at Duke University site. The rainwater is collected from roof run-off and stored in two 1000-gallon storage tanks for later use (Fig. S.1.2). The Home Depot Smart Home at Duke University site is also populated with indigenous plant species which further reduce the demand on the rainwater system.

Energy and Atmosphere

At the Home Depot Smart Home at Duke University, there is an array of 18,160-W photovoltaic panels (see Fig. S.1.3), which creates a $\sim$3-kW solar power station. The energy generated by the panels is connected to the public power grid and puts energy back onto the grid for use by the neighbors. It also reduces the total energy consumed by the Home Depot Smart Home at Duke University by approximately 30%.

Figure S.1.2 A 1000-gallon rainwater cistern at the Home Depot Smart Home at Duke University.

Figure S.1.3 Photovoltaic panels at the Home Depot Smart Home at Duke University.

Materials and Resources

All waste generated at the Home Depot Smart Home at Duke University site during construction was placed in a single bin for convenience. When the bin was collected, it was taken to a sorting facility where the waste was separated into disposables and recyclables. Using this process, more than half of the total waste was being diverted from landfills.

Indoor Environmental Quality

Research has shown that providing daylight views to building occupants increases productivity. Anecdotal evidence suggests that having access to daylight and views creates happier residents. In the Home Depot Smart Home at Duke University, greater than 90% of locations inside the building have direct daylight views.

Innovation and Design Process

The Home Depot Smart Home at Duke University is a resource for use by the university and local community for learning about sustainable building techniques. At the facility students can learn about sustainable construction techniques. Public tours are also available upon request.

The transitional model represents a significant break from the linear model and the virtual independence of each stage of development in the progression from concept to completion. Using software tools earlier in the design process to model energy consumption or the effectiveness of daylighting strategies, for example, allows specialized technical input earlier in the process, and the feedback gathered from this iterative cycle can then be used to refine the solution while the design is still malleable.

THE SYNTHOVATION/REGENERATIVE MODEL

Our view is that design is moving toward more sustainable solutions by increasing the role of teamwork to find synergies through synthesis and innovations. We call this *synthovation*: *synthesis* being the merging or integration of two or more elements, resulting in a new creation, and *innovation* being the introduction of something new—an idea, method, or device. The opposite of synthesis is analysis. Environmental programs have, for good reasons been dominated by analytical thinking. Each step in a process has been viewed as a possible source of pollution. Monitoring is an act of analysis (breaking things apart to see what is wrong). However, the environmental community is calling for more synthesis, especially as technologies such as the best available control technologies called for by the Clean Air Act are gradually being supplanted by risk-reduction approaches. In other words, emphasis in the 1990s was on the application of control technologies, but the U.S. Congress wanted to be able to determine what risk remains even after these controls are put in place. Addressing such *residual risks* requires green thinking.

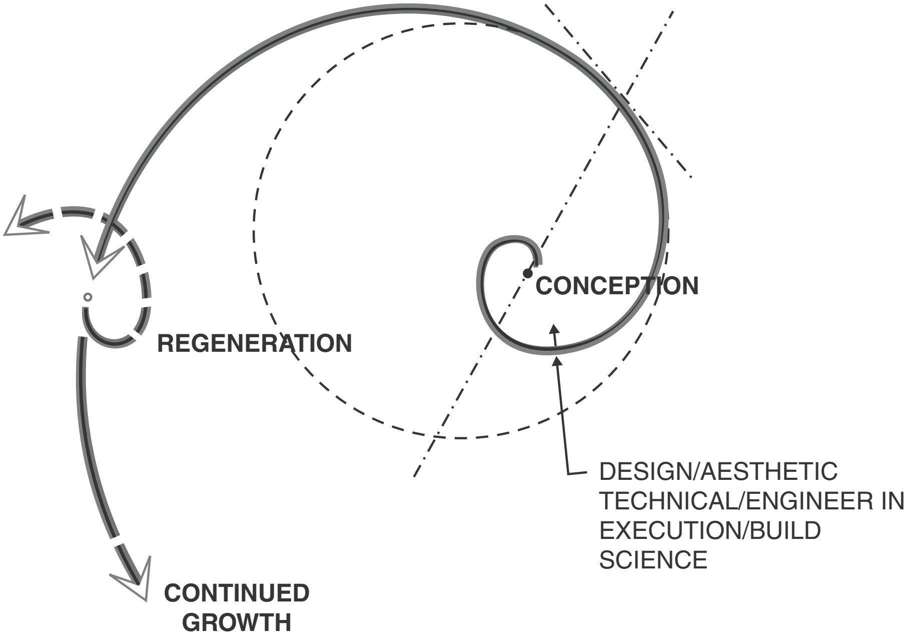
Thus, the call for innovative pollution control equipment in the twentieth century has moved to innovations in holistic design. Reducing risks in the first place harkens to the advice of business guru Peter Drucker, who has noted that innovation is "change that creates a new dimension of performance."[8] This ethos is also being expounded by designers such as John Kao, who suggests that innovation is "the capability of continuously realizing a desired future state."[9]

Emerging collaboration software tools are creating the potential for powerful synthesis and integration across technical expertise that has historically remained segregated until much later in the life of a project's development. This migration of technical input to earlier phases of the design process holds the opportunity not only for more complete synthesis but also the promise of innovation in the way we conceive and shape the built environment. As illustrated in Figure 1.5(a), the progression from concept to completion would draw from multiple expertise of the design team from the very early stages of development. The "spine" forms the path of project delivery in this case and is representative of the progress from concept to completion as the input from design, technical, and construction expertise is reflected in the growth of the concept as it evolves. The next generation of software will allow digital, rapid prototyping of alternative scenarios incorporating diverse inputs as the model grows with each successive iteration, building on the preceding cycle of input and providing a frame for continuous integration and performance improvement.

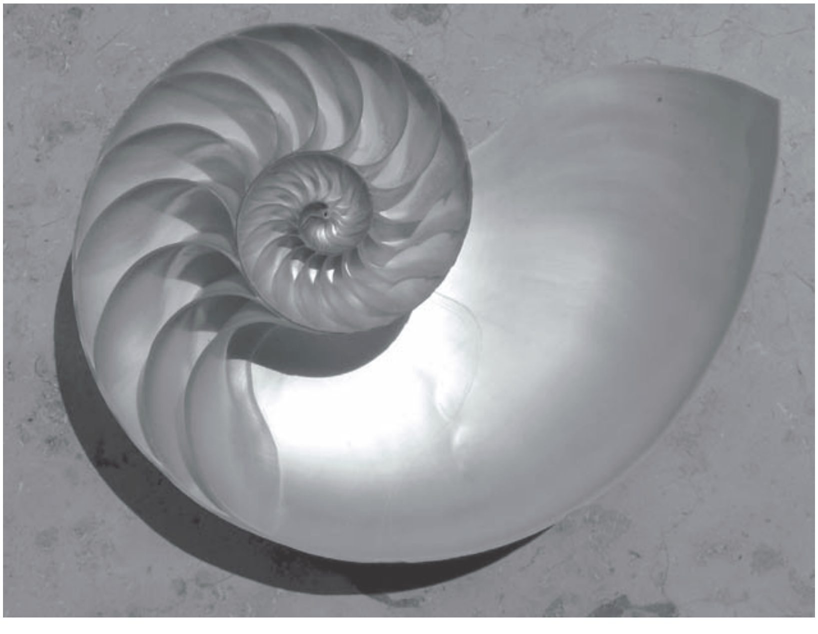
The nautilus shell [see Fig. 1.5(b)] and sunflower seed patterns provide useful analogies when describing this new model that bridges concept to completion, with multiple interlocking spirals representing the continuous iterative process and integration of multiple dimensions of technical expertise. The spiral pattern is repeated in nature in many variations, from the rotation of plant stalks to provide leaves with optimal exposure to sunlight by never occupying the same position twice, to the spiral growth pattern of a seashell, continuously expanding and maintaining optimal structural strength (see Fig. 1.6).

Figure 1.5 (a) Synthovation model adapted from the nautilus shell; (b) nautilus shell cross section.

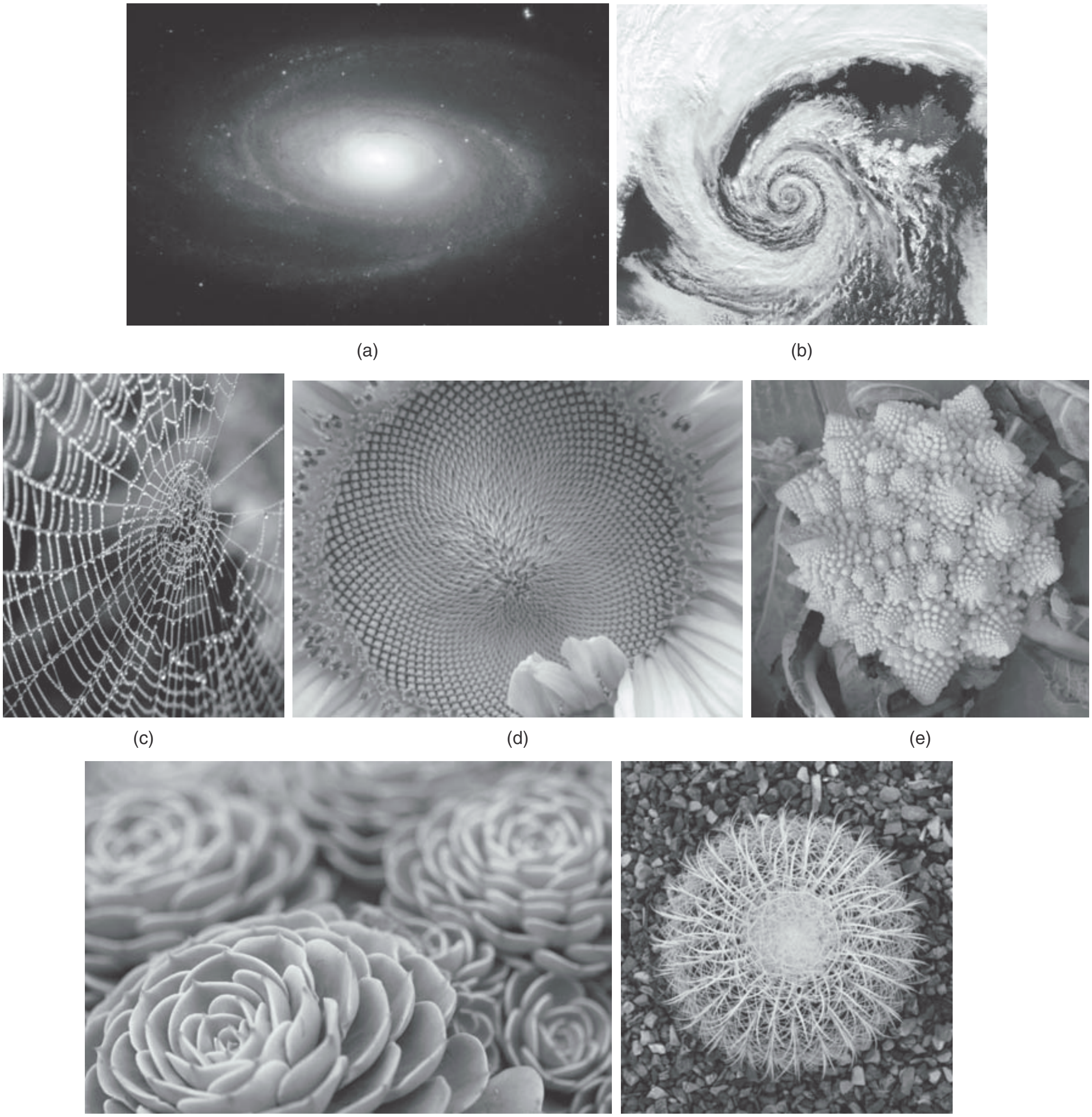
Part (b) is a Wikipedia and Wikimedia Commons image and is from the user Chris 73 and is freely available at http://commons.wikimedia.org/wiki/Image:NautilusCutawayLogarithmicSpiral.jpg under the creative commons cc-by-sa 2.5 license.



(a)



(b)



(a) (b)

(c) (d) (e)

(f) (g)

Figure 1.6 Examples of spiral forms in nature.

Credits: (a) NASA, ESA and the GMOS Commissioning Team (Gemini Observatory). (b) Jacques Descloitres, MODIS Rapid Response Team, NASA/GSFC. (c) Photo courtesy of Josef F. Stuefer, released under a Creative Commons Attribution-NoDerivs 2.0 license, http://www.flickr.com/photos/josefstuefer/9500503/. (d) Photo courtesy of robstephaustralia, released under a Creative Commons Attribution 2.0 license, http://www.flickr.com/photos/robandstephanielevy/274845180/. (e) Photo courtesy of Harris Graber, released under a Creative Commons Attribution-NoDerivs 2.0 license, http://www.flickr.com/photos/monkeyone/271662746/. (f) Photo courtesy of Nagarazoku, released under a Creative Commons Attribution-ShareAlike 2.1 Japan license, http://www.flickr.com/photos/nagarazoku/343342027/. (g) Photo courtesy of Steve Evans, released under a Creative Commons Attribution 2.0 license, http://www.flickr.com/photos/babasteve/210944351/.

The Home Depot Smart Home at Duke University: Energy Models, Feasibility Models, and Iterative Design

"One of the major missions of the Smart Home is the focus on energy efficiency and sustainable living."
—Tim Gu, *Undergraduate Student, Duke U. and Smart Home President*

The Home Depot Smart Home at Duke University is a 6000-ft^2 residential dormitory and technology research laboratory operated by the Pratt School of Engineering, Duke University.

During the design development phase of the Home Depot Smart Home at Duke University, it was very important to the team to select an overall building design that was efficient to heat and cool. To achieve this end, three models were conceived of, each highlighting different design concepts attractive to the team (see Fig. SH1.1).

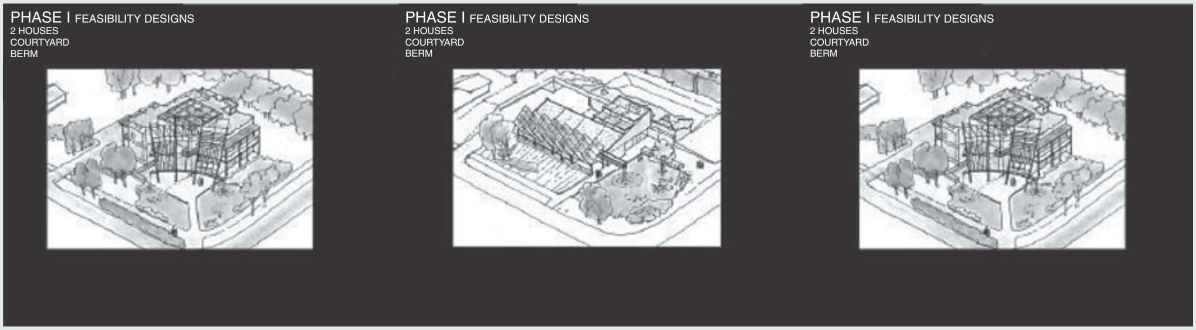


Figure SH1.1

- *Model: Two Houses.* Designed to blend with the size of the other local houses but to provide the increased square footage needed by the program for a 10-student occupancy.
- *Model: Courtyard.* Designed around the idea of having a large amount of public outdoor space available for program use. The building was built around an open area in the center.
- *Model: Berm.* Designed around the idea of having a large, south-facing test platform for experimentation with various types of solar power and heating technologies.

After all the models were created, they were each evaluated for their theoretical heating and cooling loads over the course of a year (see Fig. SH1.2). The design elements with the best energy performance synthesized into three more designs, each superior to the others. Those designs were then built into

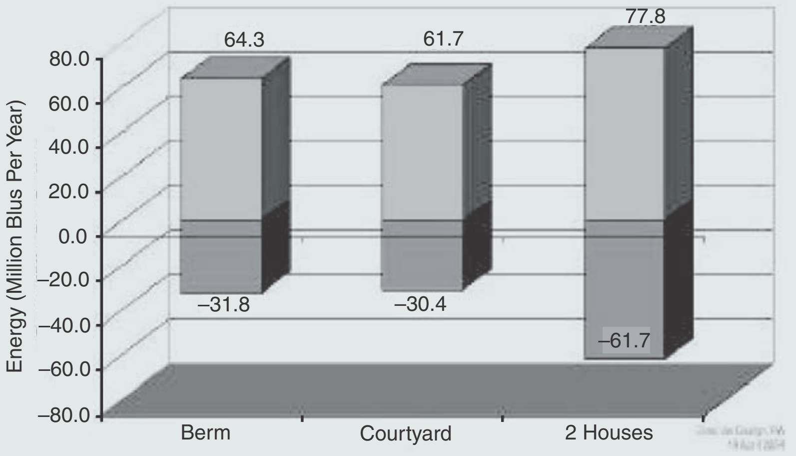


Figure SH1.2

physical models and evaluated for feasibility (see Fig. SH1.3). The keyboard model was built around the idea of having different pods for each bedroom which would be added to, removed, or expanded. The bar model was built for simplicity. It had a great surface area/volume ratio and was easy to construct. The squirrel model was designed for experimentation with different types of sun exposure as well as providing interesting aesthetic contours.

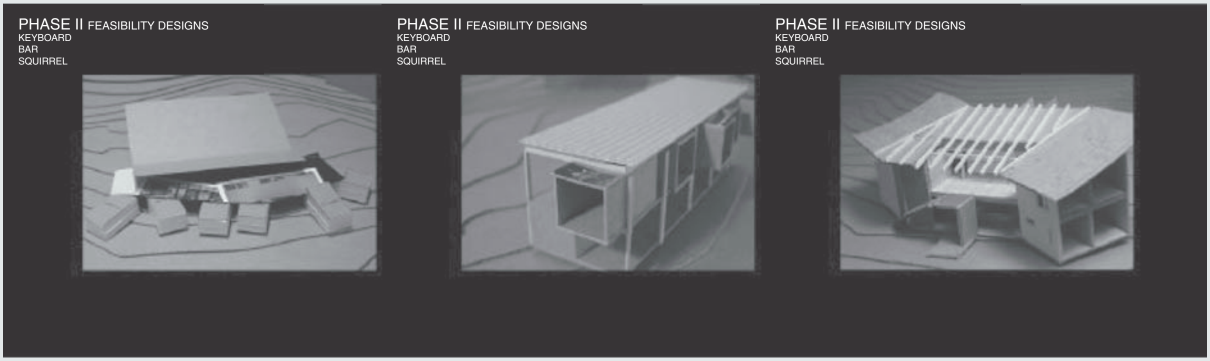


Figure SH1.3

A third design phase combined the best features of the energy and feasibility analyses and created a single design concept for what closely resembles the as-built Home Depot Smart Home at Duke University (see Fig. SH1.4).

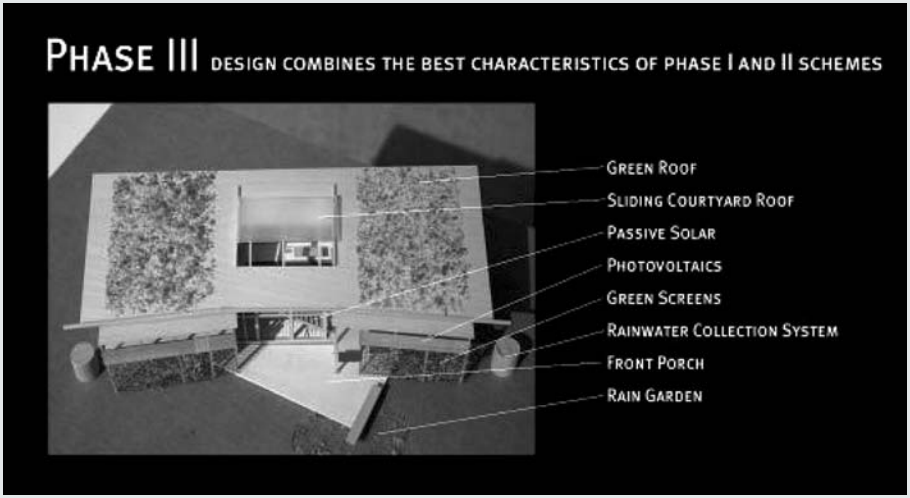


Figure SH1.4

Questions

1. Compare the ease of using the traditional stepwise design process to that of the green, iterative process in terms of incorporating energy-efficient systems and materials.
2. Consider the life cycles of a green roof compared to a traditional roofing system.
3. How might high- and low-tech solutions be merged in this design?

Source: This example was provided by Tom Rose, Director of the Duke Smart Home Program.

The design process that follows this spiral approach is preferable to the current "loops," which represent feedback. Half of the loop is retrograde. That is, the client can infer that the design is progressing, but in order to incorporate various viewpoints, it is losing ground (and costing more money and time). Often, however, a synergistic and innovative design never goes backward. In fact, better and, frequently, more cost-effective features are being integrated into the project continuously. This goes beyond the "pay now versus pay later" decision, although considerations of the entire life cycle *will* save time and money, not to mention preventing problems of safety and pollution that can lead to costs, dangers, and liabilities down the road, after completion (see Fig. 1.7).

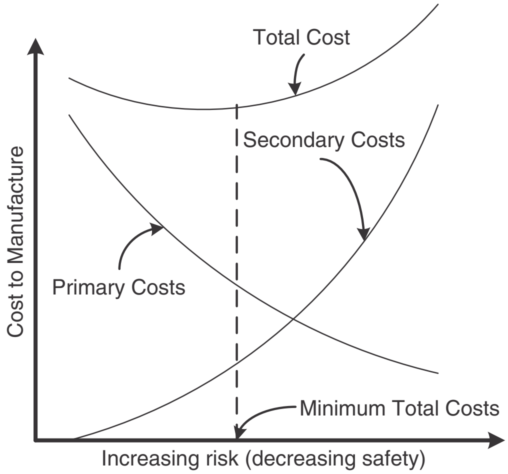


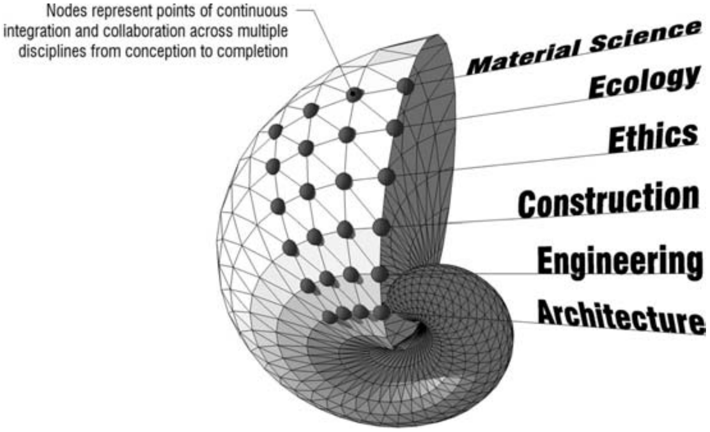
Figure 1.7 Safety and environmental risks associated with primary and secondary costs. Increased safety and sustainability can be gained by considering secondary costs in product and system design. This is the beginning of the life-cycle perspective, especially when costs and impacts are considered in addition to financial measures.

Adapted from M. Martin and R. Schinzinger, *Ethics in Engineering,* McGraw-Hill, New York, 1996.

Design software is becoming increasingly robust. We can now store parametric data that allow comparisons of various options across multiple dimensions. Design teams can rapidly develop prototype alternatives early in the process and continue to test development as solutions emerge and take form. And as we gather more data and test these models, our uncertainties will continue to decrease. Of course, we will never be completely certain about outcomes, in light of the myriad influences and variables. However, the integrated approach is much better than the brute force of a single design strategy, in which we can only hope that there will be no unpleasant surprises down the road (e.g., material and system incompatibilities, unexpected operational costs, change orders, retrofits).

Continuous improvement calls for sound science (see Fig. 1.8). New dimensions against which design alternatives will be able to be measured include the evaluation of technical inputs being proposed, as well as modeling performance against multiple variables such as climatic conditions. Returning to our living organism analogy, a design needs technical expertise to grow; thus such information is the design's "nutrients." Such technical nutrients cycle through the design process. For example, a more complete picture of energy consumption is gained by models able to look both upstream to manufacturing and transport to account for embodied energy, as well as downstream to test the digital prototype against a range of environmental conditions, not simply a static condition derived from the averages for a particular site. Consideration can also be given to the potential for regenerative design by accounting for and analysis of the technical and biological nutrients that a proposed design will consume and how easily these nutrients are able to find productive reuse in the next generation or cycle of use.

Figure 1.8 The synthovation design process depends on sound technical information and collaboration across multiple disciplines. The design critical path is influenced by the quality of information at every intersection.



THE NECESSITY FOR SYNTHESIS-INTEGRATED INNOVATION IN SUSTAINABLE DESIGN

Daniel Pink in his book *A Whole New Mind* makes the argument that humankind is at the threshold of a new era that he has coined the *conceptual age*.[10] Pink argues that success in this new era will necessitate seeking solutions that leverage the thought process of both the right and left hemispheres of the brain. He identifies six essential right-brain aptitudes necessary for the "whole new mind" that this new era will demand: (1) design, (2) story, (3) symphony, (4) empathy, (5) play, and (6) meaning.

Pink argues that these six senses will increasingly shape our world.[11] We agree. Pink has identified the need for a "symphony aptitude," which is at the heart of integrated design. This is the ability to put the pieces together, to synthesize, "seeing the big picture and, crossing boundaries, being able to combine disparate pieces into an arresting new whole."[12] Design and symphony aptitudes must be developed in order to create innovative solutions that reach beyond functional and aesthetic considerations to address environmental concerns.

This argument for discovery at the intersection of what have traditionally been compartmentalized and partitioned thought processes is counter to the twentieth century models of practice for architecture and engineering. Successful sustainable design strategies demand an integrated approach to practice in which both quantitative and qualitative considerations are valued, and provide leverage in conceiving the highest and best solutions to society's challenges in the built environment.

Sidebar: Applying the Synthovation/Regenerative Model: The Symphony of Sustainability

Symphony is a musical term. It is also a metaphor for integration and synergy. Interestingly, music has played a prominent role in environmental awareness. The environmental movement is a relatively young one. Popular culture enhanced scientific awareness of the concept of Spaceship Earth: that our planet consists of a finite life support system and that our air, water, food, soil, and ecosystems are not infinitely elastic in their ability to absorb humanity's willful disregard. The poetry and music of the 1960s expressed these fears and called for a new respect for the environment. The environmental movement was not a unique enterprise but was interwoven into growing protests about the war in Vietnam, civil rights, and general discomfort with the "establishment." The petrochemical industry, the military, and capitalism were coming under increased scrutiny and skepticism. Following the tumultuous 1960s, the musical group Quicksilver Messenger Service summed up this malaise and dissatisfaction with unbridled commercialism and a seeming disregard for the environment in their 1970 song *What About Me*. The song laments that Earth's "sweet water" has been poisoned, its forests clear-cut, and its air is not good to breathe. The songwriters also extended Rachel Carson's fears that the food supply is being contaminated, linking diseases to food consumption (i.e., "the food you fed my children was the cause of their disease").

These sentiments took hold, became less polarized (and eventually, politically bipartisan for the most part), and grew to be an accepted part of contemporary culture. For example, the mind-set of *What About Me* is quite similar to that of the words of the 1982 song *Industrial Disease*, written by Mark Knopfler of the band Dire Straits, but with the added health concerns and fears created by chemical spills, radioactive leaks, and toxic clouds produced by a growing litany of industrial accidents.

In poetic terms and lyrical form, Knopfler is characterizing the growing appreciation of occupational hazards, the perils of whistle-blowing, and the cognitive dissidence brought on by people torn between keeping their jobs and complaining about an unhealthy workplace ("Somebody blew the whistle and the walls came down . . ."). His words also appear to present a hypothesis about the connection between contaminant releases (known and unknown) and the onset of adverse effects in human populations (i.e., "Some come out in sympathy, some come out in spots; some blame the management, some the employees . . .").

Such a connection is now evident, but in the early 1980s, the concept of risk-based environmental decision making was still open to debate. These concerns were the outgrowth of media attention given to environmental disasters, such as those in Seveso, Italy and Love Canal, New York (e.g., could Knopfler's "some come out in spots" be a reference to the chloracne caused by dioxin exposure at Seveso and Times Beach, Missouri?), and the near-disaster at the Three Mile Island nuclear power plant in Pennsylvania. But Knopfler's lyrics are particularly poignant, prescient, and portentous in light of the fact that he penned these words years before the most infamous accidents at Bhopal, India and Chernobyl, Ukraine, both causing death, disease, and misery still apparent decades after the actual incidents ("Sociologists invent words that mean *industrial disease*").

Recently, musicians have embraced green and sustainable design principles.* One of the most prominent advocates is singer/songwriter Jack Johnson. Beyond lyrics, Johnson has rethought his music enterprise, including redesigning his studio, specifying green materials such as bamboo flooring and utilizing the sun as a source of energy. The band Pearl Jam required that its 2003 tour be "carbon neutral,"† and in 2005 completely switched all tour buses to run on renewable biodiesel fuel. Johnson did the same and credits many of the ideas to the older "rockers," including Neil Young and Bonnie Raitt. In our first class of first-year green engineering students at Duke, when asked about their reasons for taking the course, two mentioned that they want to combine science and engineering with music. This is further evidence of an emerging trend in whole-brain thinking of the next generation of designers.

This is also evidence that sustainable design is really not just about sustaining but about enhancing green ideas. The symphony is being played at the intersection of the two generations, and spanning once distinctly separate worlds of study.

*See "Going green," *Billboard*, http://www.billboard.com/bbcom/live-earth/green-artists.html, accessed September 2, 2007.

†Carbon neutrality is the concept that no more carbon is released than is sequestered in a given process.

MODELS FROM NATURE OF INTEGRATED SYSTEMS DESIGN

> Human subtlety will never devise an invention more beautiful, more simple or more direct than does Nature, because in her inventions, nothing is lacking and nothing is superfluous.
>
> Leonardo da Vinci
> (*The Notebooks of Leonardo da Vinci*, Jean Paul Richter, 1888)

Duke University is a leader in environmental and biomedical engineering research. Emulating nature is a prominent area of research, especially the research that is taking place in the Center for Biologically Inspired Materials and Material Systems. Nature has been extremely successful in design at a vast range of scales. The elegance of the simplicity of a virus, and the complexity of a blue whale or a giant redwood tree, testify to the efficiency and effectiveness of natural systems. So, then, what can we learn from a tree as a system that can be emulated in good design?

If we think about the tree as a design entity, it is a very efficient and effective "factory" that makes oxygen, sequesters carbon, fixes nitrogen, accrues solar energy, makes complex sugars and food, creates microclimates, and self-replicates.[13] Beyond a single tree, the ecological association and community of trees makes use of what nature has to offer. It takes up chemical raw materials (nutrients) using two subsystems, roots and stomata. Thus, the community of trees makes use of two fluids, water and air, to obtain the chemicals needed to survive. Furthermore, a collective of trees is more than just a group. A stand of 100 trees is not the same as the product of 100 times a single tree. The collective system differs from the individual tree's system. Engineers and architects can learn much from biologists, especially the concept of symbiosis. There are synergies, tree-to-tree relationships, as well as relationships between the trees and the *abiotic* components (nonliving features, such as the sand and clay in soils and the nitrogen in the atmosphere and soil water). The tree system also depends on and is affected by other living things, that comprise the biotic environment, including microbes in the soil that transform chemical compounds, allowing trees to use them as nutrients, and insects that allow sexual reproduction via pollination. So what would it be like to design a building in a manner similar to how nature shapes a tree? What are the possibilities of designing a city that is like a forest? In Chapter 7 we discuss the tree as a design component.

Principles of Biomimicry

Living systems reflect the "new" design model. In her book *Biomimicry*, Janine Benyus argues that nature presents a workable model for innovation worthy of imitation. The biomimicry model looks to nature as a learning resource rather than merely as a natural resource commodity to be extracted from the Earth. Benyus writes that "nature would provide the models: solar cells copied from leaves, steely fibers woven spider-style, shatterproof ceramics drawn from mother-of-pearl, cancer cures complements of chimpanzees, perennial grains inspired by tallgrass, computers that signal like cells, and a closed-loop economy that takes its lessons from redwoods, coral reefs, and oak–hickory forests."[14]

Nature demonstrates beautifully how scientific principles such as optimization and the thermodynamic laws are evident and interwoven in nature's community of diverse and cooperative systems. This is evidenced in Benyus's *principles of biomimicry*:

- Nature runs on sunlight.
- Nature uses only the energy it needs.
- Nature fits form to function.
- Nature recycles everything.
- Nature rewards cooperation.
- Nature banks on diversity.
- Nature demands local expertise.
- Nature curbs excesses from within.
- Nature taps the power of limits.

Innovations in material science have accelerated over the past few years with new materials that are built from science and engineering discoveries. As discussed later in Benyus's text, many innovations in material science draw inspiration from nature. For example, the study of lotus petals' ability to repel rainwater is now finding applications in "biometic paint" and in surface treatment for concrete that absorbs pollution from the air. What can the orb-weaver spider teach today's architects, engineers, and material scientists? The study of such organisms and a closer look at the chemistry underlying the transformation of flies and crickets into materials that are five times stronger per ounce than steel at room temperature could lead to a new way of conceiving and manufacturing materials and assembling them to create more sustainable environments.

EMERGING TOOLS FOR COLLABORATION, SYNTHESIS, AND INNOVATION IN DESIGN

New tools are emerging to facilitate creation of whole systems and integrated approaches through collaboration, synthesis, and innovation in the design process. In addition to supporting collaboration, new software tools are allowing designers to develop, digitally prototype, and test on demand, providing freedom to explore virtual models of alternatives quickly.

Open-Source Software

In *Massive Change*, Bruce Mau envisions a future in which we will build a *global mind*. This is made possible through the impact of emerging network protocols for distributed computing that provide for the linking of databases and the sharing of simulation and visualization tools available to anyone, anywhere. Mau notes that "to imagine that any one closed group could solve the problems we confront today is folly. The free and open software movements promise to overcome our territorial attitudes and take advantage of our collective potential."[15] Open-source software is counter to the traditional approach of source codes, which both technically and legally, protect the fundamental working structure of the software from the general public. Open-source software opens the operating system to anyone with the interest and technical ability to propose improvements or extend the capabilities of the software tool. The emergence of open-source software has led to the collaboration of a diverse collection of people bringing varied experiences and creativity to the development of these tools. *World Changing*, a collection of essays on meeting the great challenges of the twenty-first century, includes commentary on the importance of this emergence of open-source software in providing a critical design tool for collaboration. "Open-source software would, by itself, be an important tool, but the real revolution of open-source is the model itself. All around the world, people are putting the principles of open collaboration to work on all manner of projects, which transcend the world of software."[16]

ThinkCycle

At the Massachusetts Institute of Technology, a group of graduate students in the Media Lab set up an open, online structure to allow them to collaborate on design and engineering projects. This initial idea has evolved, and as the Media Lab website states, "ThinkCycle is an academic, non-profit initiative engaged in supporting distributed collaboration towards design challenges among underserved communities and the environment. ThinkCycle seeks to create a culture of open-source design innovation, with ongoing collaboration among individuals, communities and organizations around the world."[17] ThinkCycle–Open Collaborative Design provides an invitation for a diverse cross section of students and researchers to link together and synthesize solutions that build on the expertise of others participating through ongoing peer review, critique, or simply posting of ideas and suggestions. In a contribution to *World Changing*, Dawn Danby writes about ThinkCycle and notes that "we often lack the technological or contextual knowledge to effectively solve design challenges: by bringing together complementary knowledge bases, ThinkCycle created a brilliant, pragmatic model for conducting reality checks on visionary concepts and designs."[18] Danby also notes the connection between open-source software such as ThinkCycle to the work of Victor Papanek, the UNESCO designer who refused to patent any of his works but rather, focused on creating a "public domain of form and function."[19]

BIM Tools

Tools are now available to both architect and engineer to conceive and deliver design solutions in a more integrated manner. *Building information modeling* (BIM) uses computer technology to create a virtual multidimensional models of a building as an integrated part of the design process, not as an afterthought for use in marketing the design as a finished product (see Fig. 1.9).

This approach is revolutionary in the design professions. Most design software used in architectural/engineering offices since the introduction of computer-aided design systems has represented productivity gains through increased efficiency but really has not represented major advances beyond digitally representing primitive lines, arcs, and circles to define buildings.

Designers using BIM software can apply digitally bundled information called *objects* to represent building components such as windows and doors. These models are enriched by their ability to represent a much wider range of information on the physical characteristics of the building. The potential for these models to behave in an "intelligent" manner provides the opportunity for exploration and collaboration among design disciplines as well as with the construction community. The term *integrated practice* has been coined to describe this approach, which represents both an opportunity and a challenge for the architecture and engineering professions.

Better quality, greater speed, and lower cost by way of improved efficiency can be expected from the BIM approach. From a sustainable design perspective, the greatest potential is for increased collaboration and integration across design disciplines supporting the promise of a trend toward systems solutions similar to those found in nature. This allows the designer to envision positive and negative outcomes of various options. The BIM process is also a tool for moving beyond the stepwise model, in that it requires that issues which historically have been addressed exclusively during the development of construction documents be discussed during the design phases. Recently, Carl Galioto, FAIA, a partner at Skidmore, Owings & Merrill in New York, noted that "BIM will change the distribution of labor in the design phases. When done correctly, the labor is front loaded earlier in the design process, during schematic and design development phases, and less in construction documents."[20] This shift in the labor distribution is consistent with Pink's notion of value-added input occurring during the early phases of the conceptual development of design.

(a) (b)

Figure 1.9 Building information modeling uses computer technology to create a virtual model of a building as an integrated part of the design process. (a) The design of the Pearl River Tower designed by Skidmore, Owings & Merrill, LLP. for construction in Guangzhou, China, includes integrated wind turbines and photovoltaic panels to offset its energy use. (b) Ecotect model showing the amount of solar radiation on the tower's various surfaces.

From "Building information modeling and green design feature," *Environmental Building News,* May 2007. Rendering.

These information-rich models provide the ability to simulate and analyze alternative scenarios that incorporate project specifics such as local climate that are critical to finely tuned sustainable design strategies. This ability to test design via simulation provides the architect and engineer with a more complete understanding of the ramifications of their designs across multiple measures of performance. While the models provide the ability to advance beyond two-dimensional representation to create three-dimensional space models as found in other recent software programs, the BIM models also have the ability to introduce multiple new dimensions into the design process, including time, cost, procurement, and operations. By leveraging the additional information provided in these new dimensions, a more robust database and an adaptive expert system are available to the design team to explore and conduct more comprehensive life-cycle cost models.

INTEGRATION AND COLLABORATION

To be an architect, engineer, or designer is to be an agent of change, and by working collaboratively, we have the potential to become the alchemists of the future, transforming a collection of data and myriad inputs to derive designs that protect and shape our environment in a manner that benefits all. The amount of "lead" is increasing exponentially, but the opportunities for "gold" (innovation) are also rapidly growing. We may be tempted to take short cuts, but we must remain steadfast in search of sound designs. The common thread is adherence to nature's rules as codified in scientific principles. There is no substitute for sound science in green design. That is our focus in Chapter 2.

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chapter 2

First Principles

THE CASCADE OF SCIENCE

When science finds its way to the front page of the newspaper, or to the movie theater box office, or to the office water cooler, it is often both a blessing and a curse. We live in a time when explanations often lack the rigor and attentiveness that scientists can bring to important topics. The scientific method is based on the patience and progression of observation and experimentation. Its explanations are supposed to be circumscribed and exclusively fact based. Variables are controlled. All plausible hypotheses must be considered before scientists are comfortable with ascribing a cause.

Unfortunately, the popular press and most people, especially those whose lives do not revolve around science, will not sit idly waiting for this thorough and abiding process to run its course. Even fellow scientists grow weary waiting for a long-term study to be completed and are tempted to release "preliminary results" that may have not undergone appropriate peer review. Also, those reporting the results—the lay public, media, and even scientists—often do not include all of the caveats and contingencies intended by the scientists who conducted the studies.

No current issue is more fraught with this dichotomy than is *sustainability*. Many who use the term have little understanding of its meaning. Even fewer understand the scientific principles that underpin widely held opinions. This is apparent in the science of global climate change. As shown in Figure 2.1, to understand changes in climate and what can be done to mitigate damage requires a cascade of knowledge, all underpinned by physics, followed by chemistry, followed by biology, followed by engineering, followed by policy decisions, followed by the collective of personal choices.

Most "big" issues must be approached by a three-step strategy that addresses (1) awareness, (2) decision making, and (3) behavior. Films such as *An Inconvenient Truth* and even missives from the Intergovernmental Panel for Climate Change

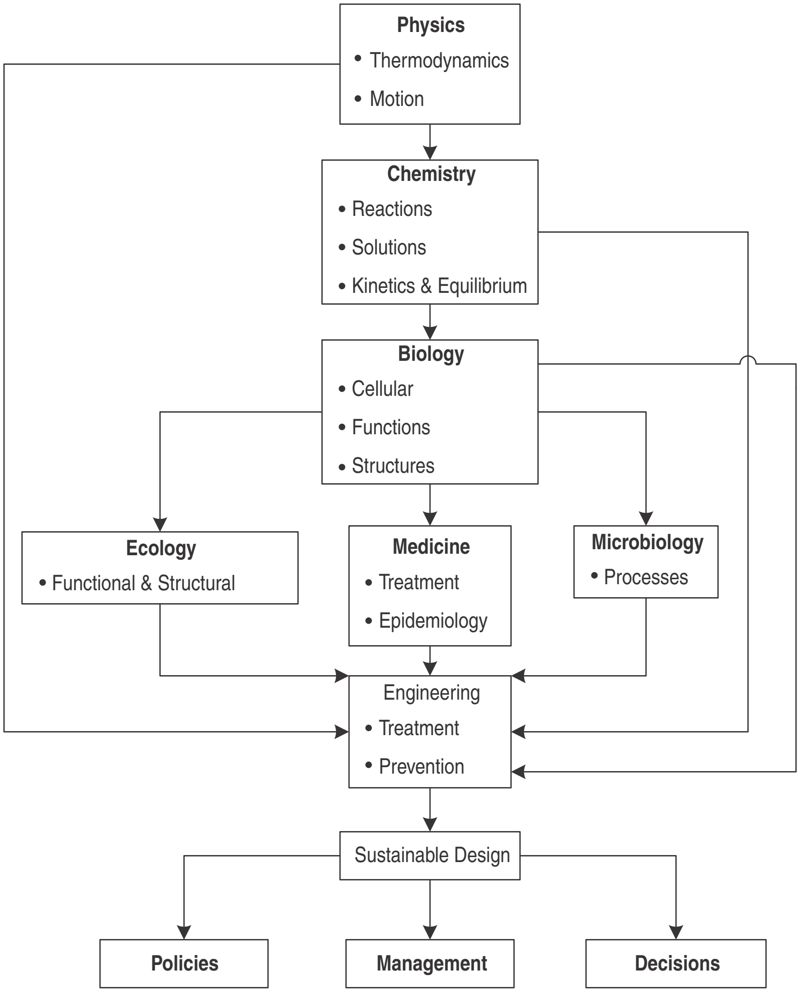


Figure 2.1 The cascade of sciences that lead to a sustainable decision. Each lower box depends on the quality of every box above it, so that uncertainties and variability must be considered with each progression.

help to shape the first step, *awareness*. This step is messy and tries to reach unanimity, or at least consensus. Physics is more comfortable with unanimity. It is best if *all* credible physicists agree on something. For example, most agree on the properties of heat flux, mass balance, and other thermodynamic principles. They may hold diverse opinions as to why thermodynamic processes occur from an elementary, subatomic perspective, but they agree on the empirical explanations of the processes. The same goes for chemistry. We agree about electronegativity, polarity, and reduction–oxidation, even though we do not necessarily agree about the role of quantum mechanics in these processes. Biology also requires rigorous application of physical and chemical principles. As such, it is a "derived" science, with greater uncertainty and variability than those of empirical physics and chemistry. Life systems are complicated. Cause-and-effect relationships are complex.

The problem with increasing awareness is that it is often not well behaved. We tell people that a model indicates that carbon dioxide increases of *x* megatons will lead to warming of 1°C each decade, which could lead to melting of glaciers and ice caps. What is not shown are the confidence intervals around the estimates, nor the assumptions in the model that led to the result. For example, the internal dependencies of the model are not shared or are ignored. We assume that the presence of so much greenhouse gas will influence the greenhouse effect in Earth's atmosphere, which in turn will increase the mean Earth temperature. We also assume that the temperature increase will be distributed in such a way that the melting will occur that is feared. It is quite possible that the scientists include all of these assumptions (although I have heard some who have not) in their reports to the media, but the reporter did not consider these "details" to be newsworthy. So great care must be taken to ensure that what people are becoming aware of is, in fact, what the science is saying.

This awareness step should be familiar to the design professional, who may have difficulty keeping the client focused on the numerous, diverse details of a design. The client may want to skip to the bottom line. What is the project cost? What will the structure look like? When will it be built? It may only be after the client is unhappy about any of these that the designer can explain the science behind a design. For example, the materials needed to provide the function requested by the client are expensive. Or, the open floor design may be incompatible with servicing needs. Or, the schedule has some internal dependencies that cannot be built in parallel, but must be serial.

This brings us to *decision making*. Given that we have done a good job of raising awareness, the science should drive decisions. Often, this gets out in front of awareness. We may not fully understand the problem or we may be pushed toward a decision for reasons other than science. For example, is the dwindling habitat of the polar bear an established fact? Or is it sufficiently sensational that we *should* do something, no matter the state-of-the-science? This is a very interesting challenge. For example, much of the world community has shifted toward the *precautionary principle* for big decisions much as those revolving around global climate change. Others, including the United States, rely mainly on a *risk-based decision approach*. The difference is "onus". The precautionary principle places the onus on what could happen. For example, a new product is approved only if the company claims that it can prove it to be safe. Conversely, the risk-based approach places the onus on regulators to ask the right questions and to disapprove the product only if based on available evidence, it presents an unacceptable risk.

The last step in decision strategy is *behavior*, the subject of this book. Our belief is that the practicing professional can better ensure green designs and sustainable solutions in everyday practice, and we contend that success is more likely with a proper explanation of *why* one's designs are green. That is, we not only want to offer green designs but also to give reasons for their being green. Throughout the book, when a technique or guide is given, it is accompanied by a scientific explanation of how it works. In particular, two sets of first principles must form the basis of all sustainable designs: the laws of thermodynamics and motion.

Physics

Physics concerns itself with matter, energy, motion, and force. Arguably, all other sciences are simply branches of physics. Even chemistry, which is the science that deals with the composition, properties, transformations, and forms of matter, is merely a discipline within physics. Therefore, we will not draw "bright lines" between physics and chemistry. Often, in this book and elsewhere, the dichotomy is avoided by using the term *physicochemical* to address properties and characteristics that are included in both physics and chemistry. Therefore, force, velocity, flow rates, discharge, and friction are clearly terms of physics. Similarly, redox, acidity–alkalinity, stoichiometry, and chirality are terms of chemistry. However, kinetics, sorption, solubility, vapor pressure, and fugacity are physiochemical terms. In green engineering and sustainable design, we are clearly concerned with how underlying principles of thermodynamics and motion affect our projects.

Thermodynamics

Thermodynamics is the science of heat (Greek: *therme* = heat; *dynamis* = power). In particular, it addresses changes in temperature, pressure, and volume in macroscopic physical systems. Heat is the transfer of thermal energy between bodies that are at different temperatures. In the process of such transfer, movement occurs. For example, heat transfer leads to the turning of the wheels of an automibile, or the movement of air through a building. We discuss motion as a separate scientific underpinning of design. However, it is important to keep in mind that thermodynamics is concerned with the transformation of heat into mechanical work and of mechanical work into heat.

The principles of potentiality link thermodynamics and mechanics (and hence green engineering's concern with efficiencies of motion). That is, thermodynamics is concerned with the flow of heat from a hotter body to a colder body. Other potentials important to green engineering include elevation (flow from higher elevation to lower elevation, i.e., the engineering concept of *head*), and electricity (voltage difference between two points, toward the ground, where voltage = 0). These differentials make for motion. Water flows downhill, charge moves toward the ground, and heat transfer is from higher to lower temperatures. Thus, thermodynamics underlies mechanics.

Systems

Note that when we introduced thermodynamics, we mentioned that it applies to macroscopic systems. Macroscopic scale is somewhat arbitrary, but it certainly is larger than a single molecule and usually includes a large number of molecules as the domain of heat relationships. As observed in recent nanotechnological research, physical behavior can be quite different at small scales. For example, the current distinction between nanoscale and bulk-scale systems is 100 nanometers (nm). In other words, if a particle has a dimension <100 nm, it is considered to be at the nanoscale. Electromagnetic properties can be quite different at the nanoscale than at the macroscopic scale. In some cases, the emission of energy, such as light, can be altered significantly (witness that some nanoparticles of gold are red in color, not gold).

A *system* has two definitions that apply to green engineering:

1. Generally, a system is a combination of organized elements comprising a unified whole.
2. From a thermodynamics perspective, a system is a defined physical entity containing boundaries in space, which can be open (i.e., energy *and* matter can be exchanged with the environment) or closed (no energy or matter exchange).

The system is what we care about, what we want to study. It may seem obvious, but in science we must distinguish what we are interested in from everything else. In physics, we do this by way of the system. What we want to study, explain, or test is in the system. Everything else is what we call the surroundings (see Fig. 2.2).

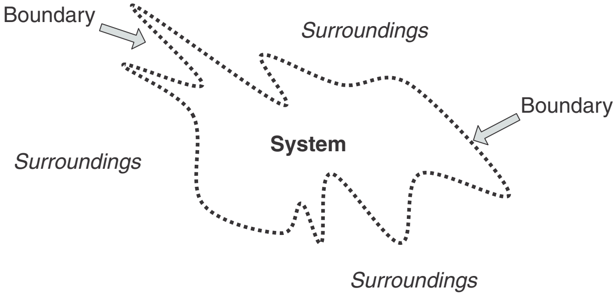


Figure 2.2 Thermodynamic system.

Also seemingly obvious is what separates the system from the surroundings: the *boundary*.

Systems are classified into two major types: closed and open. Both exist and are important in the environment. A *closed system* does not allow material to enter or leave the system (engineers refer to a closed system as a *control mass*). An *open system* allows material to enter and leave the system. Such a system is known as a *control volume*. Two control volumes that are commonly considered in green design are the organism and a defined volume around the organism. Thus, scientists commonly calculate mass balances for the classic control cube and adapt it to the environment (see Fig. 2.3). The human body is a control volume. For example, physiologically-based pharmacokinetic models (called *PBPK models*) consider the amount of a contaminant or nutrient entering a body, its changes, and the amount leaving the body. By definition, this is a control volume. Each of these volumes meets the same criteria as those for the cube in Figure 2.3, fully accounting for the mass in and out, as well as the processes that occur within them.

A few special thermodynamic considerations must be taken into account when dealing with an organism as a control volume. *Body burden* is the total amount of the contaminant in the human body at a given time of measurement. This is an indication of the behavior of the contaminant in the control volume (i.e., the person). Some contaminants accumulate in the body and are stored in fat or bone, or they simply are metabolized more slowly and tend to be retained for longer periods. This concept is at the core of PBPK models. These models attempt to describe what happens to a chemical after it enters the body, showing its points of entry, its distribution (i.e., where it goes after entry), how it is altered by the body, and how it is ultimately eliminated by the body. This is almost identical to the processes that take place in a stream, or a wetland, or other system.

In our freshman green engineering course at Duke, for example, one of the studios addresses the indoor environment. In variably the students are concerned about volatile organic compounds (VOCs) as a group. However, upon further investigation, they find that VOCs vary considerably in how they behave in buildings and in organisms (including humans).

The building is an important focus of green engineering and sustainable design. Recently, engineers and scientists have applied mass balance approaches to the individual home. Unlike the well-defined boundary conditions of the small control volume, a home has numerous inflows and outflows as well as sources, sinks, and transformation reactions. Some are shown in Figure 2.4. Modeling these dynamics is useful in estimating the exposure of people to toxic substances. Thus, to design a building properly, a thorough understanding of systems is essential.

Another thermodynamic concept is that of *property*. A property is some trait or attribute that can be used to describe a system and to differentiate that system

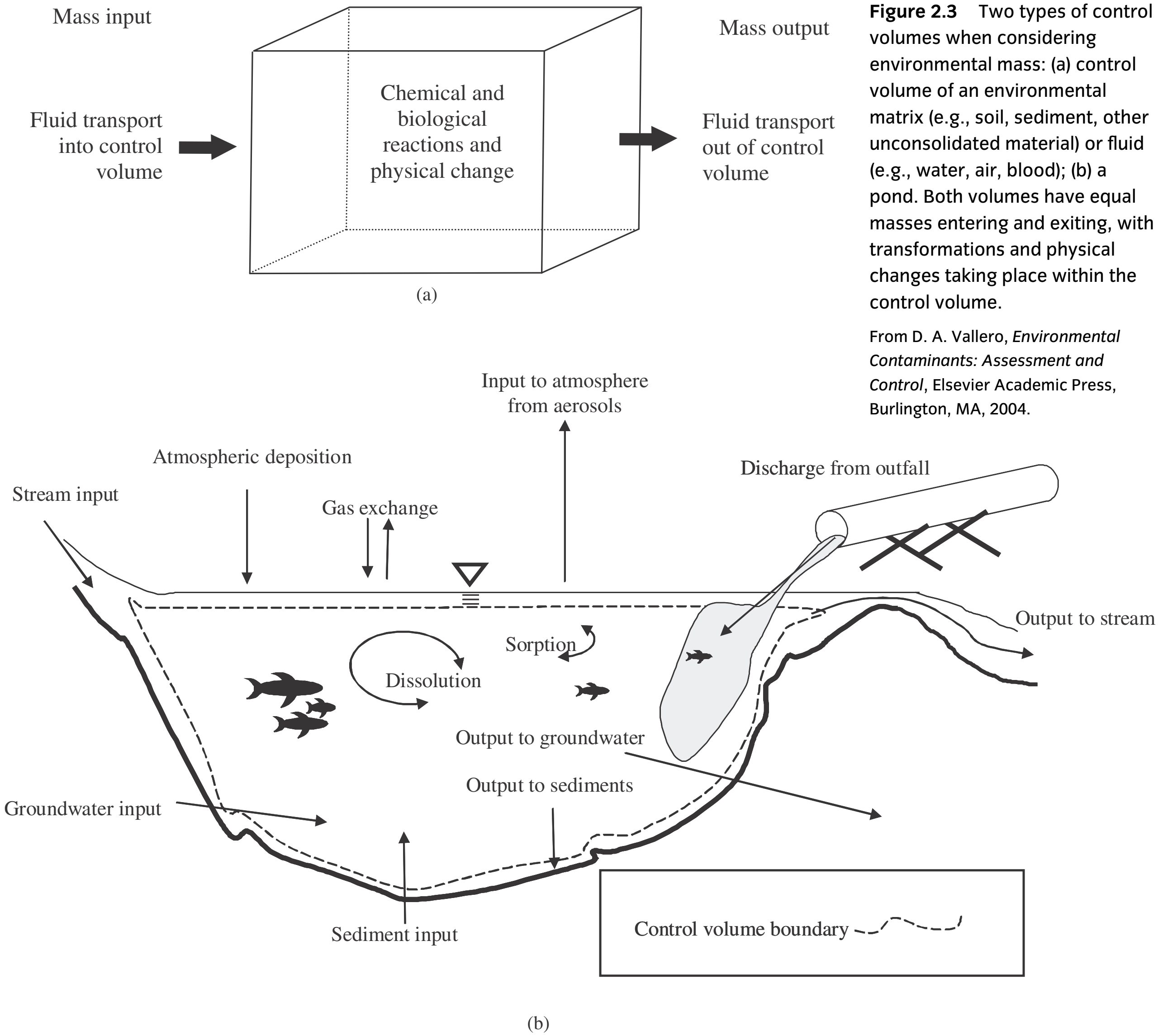


Figure 2.3 Two types of control volumes when considering environmental mass: (a) control volume of an environmental matrix (e.g., soil, sediment, other unconsolidated material) or fluid (e.g., water, air, blood); (b) a pond. Both volumes have equal masses entering and exiting, with transformations and physical changes taking place within the control volume.

From D. A. Vallero, *Environmental Contaminants: Assessment and Control*, Elsevier Academic Press, Burlington, MA, 2004.

from others. A property must be able to be stated at a specific time independent of its value at any other time and unconstrained by the process that induced the condition (state). An *intensive property* is independent of the system's mass (such as pressure and temperature). An *extensive property* is a proportionality to the mass of the system (such as density or volume). Dividing the value of an extensive property by the system's mass gives a *specific property*, such as *specific heat, specific volume,* or *specific gravity.*

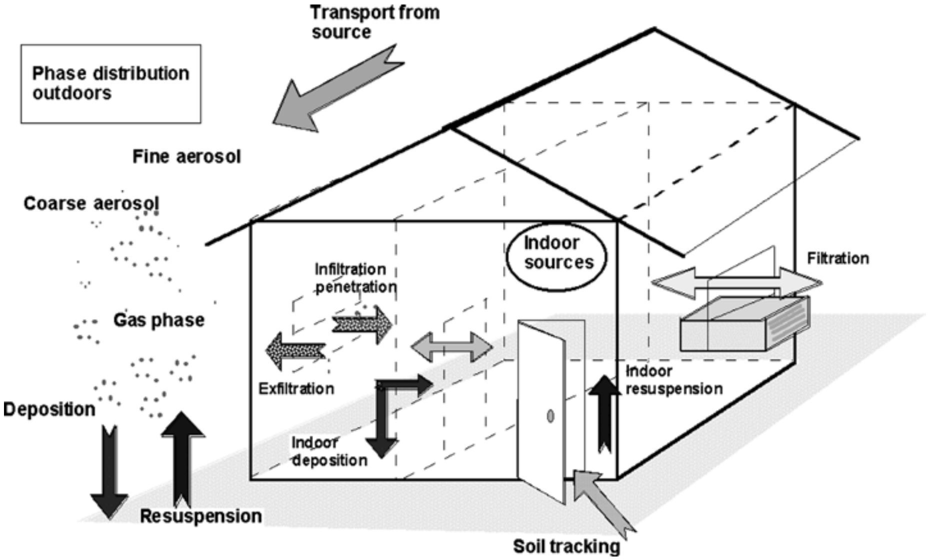


Figure 2.4 The building as a control volume. Note the various ways that contaminants can enter the volume and the numerous physical and chemical mechanisms that can transform the material that enters.

From U.S. Department of Energy, Lawrence Berkley Laboratory, http://eetd.lbl.gov/ied/ERA/CalEx/partmatter.html, 2003.

The thermodynamics term for the description of the change of a system from one state (e.g., equilibrium) to another is known as a *process*. Processes may be reversible or irreversible, and they may be adiabatic (no gain or loss of heat, so all energy transfers occur through work interactions). Other processes include isometric (constant volume), isothermal (constant temperature), isobaric (constant pressure), isentropic (constant entropy), and isenthalpic (constant enthalpy).

Thermodynamic terms are crucial to engineers, architects, and other design professionals working collaboratively with them. For example, you may attend a seminar or meeting where the engineer refers to conditions. Often, these are of two types: initial conditions and boundary conditions. You may also hear the terms *assumptions*, *constraints*, and *drivers*. These are all rooted in thermodynamics. An *initial condition* is where we start. For example, differential equations require an initial condition before calculating changes. A *boundary condition* is imposed on the solutions of differential equations to fit the solutions to the actual problem. In models, the boundary conditions describe what is expected to occur along the edges of the simulation region. Thus, initial and boundary conditions are similar to Figure 2.2. However, instead of the system within the boundary, the region inside the boundary is what is explained by the differential equation, and the boundary is where this is no longer valid (i.e., the boundary value given along the boundary curve). Everything outside the boundary is not explained by the differential equation, analogous to the thermodynamic surroundings. *Constraints* are those factors that must be considered as part of what could affect the energy transfer or changes within the boundaries. *Drivers* are those factors that make things happen. They push a system in one direction or another, such as increased heat, transfer across boundaries, energy conversions, mass transfer, and flow. Constraints and drivers can be seen as working in opposite directions.

For example, if we set our boundary at a microscopic, cellular membrane, the drivers and contraints will include the ability of a nutrient or contaminant to enter and change within the cell. However, if we look at the same chemical compound in a building, the boundaries will be the roof, floor and walls, the drivers and constraints will include air movements, porosity and permeability of the building materials, and the case of sorption to surfaces.

Motion

The second set of scientific principles that must underpin good green design concerns mechanics. Sir Isaac Newton described motion in three basic laws. For design purposes, as in thermodynamics, we are concerned almost exclusively with macroscopic scales (i.e., a large number of molecules). The *first law* states: Every object in a state of uniform motion tends to remain in that state of motion unless an external force is applied to it.

Galileo also observed this phenomenon, which he called *inertia*. This is very important for designers. If we are going to harness energy, we need to understand that objects will stay in motion unless other forces come to bear. The most common external force that changes the state of uniform motion is friction. Thus, any design must see friction as the “enemy” if we want to keep things going (lubricants and smooth surfaces are needed to fight friction), and as an essential “friend” if we want to change direction or stop things (e.g., brake shoes in an automobile).

The *second law* of motion states: The relationship between an object’s mass m, its acceleration a, and the applied force F is $F = ma$. Acceleration and force are vectors, wherein the direction of the force vector is the same as the direction of the acceleration vector.

With the second law, we can calculate unknowns from knowns. That is, if we know the mass of the propellers and the applied force generated by the wind, we can calculate the acceleration of the propellers in a windmill. This, in turn, allows us to estimate the amount of energy being generated by the windmill system.

The *third law* of motion tells us that for every action there is an equal and opposite reaction. Like the first law, this tells us that we can expect things to happen in response to what we do. If we apply a force, there will be an equal force in the opposite direction.

GREEN MECHANICS

Mechanics is the field of physics concerned with the motion and equilibrium of bodies within particular frames of reference. Green engineering makes use of the mechanical principles in practically every aspect of pollution: from the movement of fluids that carry contaminants, to the forces within substances that affect their properties, to the relationships between matter and energy within organisms and ecosystems. Engineering mechanics includes statics and dynamics. Fluid mechanics and soil mechanics are two particularly important branches of mechanics to the environment.

Statics is the branch of mechanics that is concerned with bodies at rest with relation to some frame of reference, with the forces between bodies, and with the equilibrium of the system. It addresses rigid bodies that are at rest or moving with constant velocity. *Hydrostatics* is a branch of statics that is essential to environmental science and engineering in that it is concerned with the equilibrium of fluids (liquids and gases) and their stationary interactions with solid bodies, such as pressure. Although many fluids are considered in green engineering, the principal fluids are water and air.

Dynamics is the branch of mechanics that deals with forces that change or move bodies. It is concerned with accelerated motion of bodies. It is an especially important science and engineering discipline because it is fundamental to an understanding of the movement of contaminants through the environment. *Dynamics* is sometimes used synonymously with *kinetics*. However, we will treat kinetics as one of the two branches of dynamics, the other being kinematics. Dynamics combines the properties of the fluid and the means by which it moves. This means that continuum fluid mechanics varies by whether a fluid is viscous or inviscid, compressible or incompressible, and by whether flow is laminar or turbulent. For example, the properties of the two principal environmental fluids, water in an aquifer and an air mass in the troposphere,* are shown in Table 2.1.

Table 2.1 Contrasts between Plumes in Groundwater and the Atmosphere

	Groundwater Plume	Air Mass Plume
General flow type	Laminar	Turbulent
Compressibility	Incompressible	Compressible
Viscosity	Low viscosity (1×10^{-3} kg m^{-1} s^{-1} at 288 K)	Very low viscosity (1.781×10^{-5} kg m^{-1} s^{-1} at 288 K)

---

*The troposphere is the lowest part of the earth's atmosphere, where living creatures live. Thus, this is the predominant focus of green engineering. However, spacecraft and other artificial environments have been the focus of sustainable designs

When the forces acting on a body balance one another, the body is at rest. Let us briefly consider static equilibrium of particles and rigid bodies and discuss other statics concepts, including moments of inertia and friction, which are fundamental to green design.

Environmental Determinate Statics

For a rigid body to be stationary, it must be in *static equilibrium*, which means that no unbalanced forces are acting on it. Pardon the double negative, but this is a rare occasion when stating something positively loses some of its meaning. "a rigid body having balanced forces acting on it" is not the same as "a rigid body having no unbalanced forces acting on it."

One of the key concepts in statics that is important to environmental science and engineering is force. A push or pull by one body on another body is known as a *force*. A force is any action that has a tendency to alter a body's state of rest or uniform motion along a straight line (we discuss Newton's laws regarding these concepts when we address dynamics and kinetics). Forces come in two major types, external forces and internal forces. *External forces* on a rigid body result from other bodies. An external force may result from physical contact with another body, known as *pushing*, or from the body being in close proximity, but not touching, the other body, such as gravitational and electrical forces. When the forces are unbalanced, the body will be put into motion. *Internal forces* are those that keep the rigid body in one piece. As such, these are compressive and tensile forces within the body that can be found by multiplying the stress and area of a part of the body. Internal forces never cause motion but can lead to deformation. Since force has both magnitude and direction, it is a vector quantity, so let us discuss vectors briefly as they apply to determinate statics.

The Home Depot Smart Home at Duke University: Rain Screen and Building Wrap

From ancient times, the concept of *shelter* has been an expression of fluid dynamics. Water and air are essential for life, but we need barriers against these fluids. In fact, our homes have "skins" that selectively allow in air while keeping water in its liquid state at bay. The Home Depot Smart Home at Duke University has an exterior sheathing called a *rain screen* (see Fig. SH2.1). The primary function of the home's exterior sheathing is to prevent water from penetrating the exterior walls. A rain screen is based on two lines of defense from moisture penetration. The first is intended to minimize (although not totally eliminate) the passage of rainwater into the wall. The second is designed to intercept all

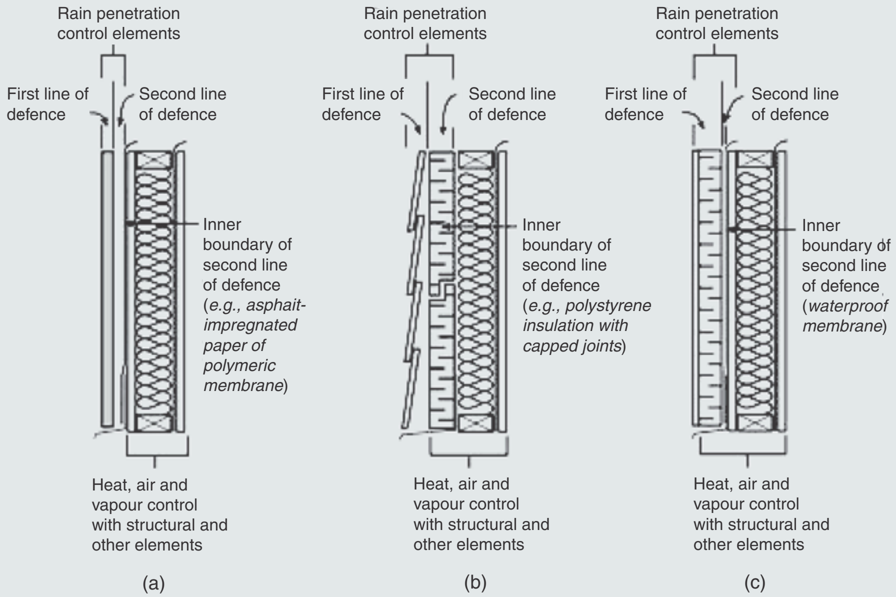


Figure SH2.1 Examples of a rain screen system and traditional exterior sheathing. Note how the rain screen leaves an airgap to allow for moisture dissipation.

water that makes it past the first layer and to dissipate it adequately back to the exterior.

The primary difference between a rain screen and a traditional exterior sheathing is the anticipation that some water will penetrate the cladding and will require dissipation back outside the wall. With a traditional exterior sheathing, water will often penetrate a crack or other breaks between two impermeable surfaces and become trapped inside a wall space, causing long-term damage to the wall, as well as an ideal condition for the growth of mold and bacteria.

Because buildings with rain screens anticipate penetration of water to their second line of defense, it is very important to select a competent product based on its ability to repel water on a regular basis. This second line of defense is called a *building wrap*, a flexible sheet that can be molded to the contours of a building and easily cut to specific customized shapes.

Examples of building wraps that were considered for use in the Home Depot Smart Home at Duke University are Vaproshield, Tyvek Homewrap, Tyvek Commercialwrap, Grace Ice and Water Shield, and No. 15 asphalt felt. Important factors for selecting a building wrap include air penetration, bulk water holdout, vapor permeability, ultraviolet (UV) exposure tolerance, and whether they are certified as a weather-resistive barrier:

- *Air penetration*. Rain screens benefit from having a building wrap with low air penetration because when air penetrates the exterior sheathing of a building, it can create a pressure gradient that drives water into and through the exterior wall into areas not designed to handle water penetration. Rain screen systems therefore require a building wrap with low air penetration. Air penetration rates lower than 0.004 cfm/ft^2 at 75 Pa are considered acceptable. This is measured using standard ASTM E2178.*
- *Water resistance*. The primary function of the building wrap is to stop any water that reaches it from passing through to the other side. Water resistance is measured as a function of the pressure required to drive water through a fabric. Water resistances at hydrostatic pressures greater than 55 cm of water are considered acceptable. This is measured using AATCC test method 127.
- *Water vapor transmission*. The purpose of a rain screen system is to allow for the dissipation of water back to the outside if it has penetrated. High rates of water vapor transmission are therefore desired. Water vapor transmission rates greater than 20 perms† are considered acceptable. This is measured using standard ASTM E96M-05.
- *UV exposure tolerance*. Because part of the Home Depot Smart Home at Duke University building wrap might be exposed to sunlight, it was important to use a material that has a high tolerance for ultraviolet (UV) light exposure without breaking down. This was not measured using a standardized test. Instead, manufacturer data were relied upon in the comparative analysis.
- *Certification of building code compliance*. Some, but not all, building wraps are certified by a national organization to show that they meet building codes as a water-resistive barrier.

These factors are compared in Table SH2.1 Tyvek Commercialwrap was chosen for its superior air penetration rate, bulk water holdout rate, vapor permeance rate, tolerance for UV exposure, and certification by a national organization for meeting building code as a water-resistive barrier.

*ASTM International, formerly the American Society for Testing and Materials, is a voluntary standards development organization.

†Permeability is a measure of the amount of water vapor (moisture) that can pass through a specified material in a certain amount of time. The measure and degree of permeability is expressed in units referred to as perms. A list of the various ASTM testing procedures can be found at http://omnova.com/products/wallcovering/perm_test.aspx

Table SH2.1 Building Wrap Selection Criteria for the Home Depot Smart Home at Duke University, Including Test Method

Building Wrap Product	Air Penetration (cfm/ft^2 at 75 Pa) by ASTM E2178	Water Resistance (cm) by AATCC-127	Vapor Transmission (perms) by ASTM E96	UV Exposure Tolerance (days)	Water-Resistive Barrier by ICC/ASTM d226
Vaproshield	0.002	68	212	UV stable	ICC ES Certified
Tyvek Homewrap	0.007	210	58	120	ICC ES Certified
Tyvek Commercialwrap	0.001	280	28	270	ICC ES Certified
Grace Ice and Water Shield	n/a[a]	n/a	0.05	30	n/a
No. 15 asphalt felt	n/a	52	8	n/a	yes
Recommended for rain screen	<0.004	>55	>20	Low or no degradation	Required

[a] n/a, not available.

Questions

1. How does this material selection process differ under the traditional stepwise design process and the integrated green design process? How may the criteria be applied using computer models (e.g. BIM)?
2. What other types of passive and active systems can be used to design building wraps?
3. How might sensors be used to enhance these processes?

Resources

ASTM E2178: http://www.astm.org/cgi-bin/SoftCart.exe/DATABASE.CART/REDLINE_PAGES/E2178.htm?L+mystore+pyfx6202
Rain Screen prose: http://irc.nrc-cnrc.gc.ca/pubs/ctus/34_e.html
AATC test method 127-2003: http://www.aatcc.org/Technical/Test_Methods/scopes/tm127.cfm
AATC E96M-05: http://www.astm.org/cgi-bin/SoftCart.exe/DATABASE.CART/REDLINE_PAGES/E96E96M.htm?L+mystore+bfks2207
ICC-ES reports: http://www.icc-es.org/

Source: This example was provided by Tom Rose, Director of the Duke Smart Home Program.

In physics, we need to distinguish scalars from vectors. A *scalar* is a quantity with a magnitude but no direction. A *vector* has both magnitude and direction. A vector is a directed line segment in space that represents a force as well as a velocity or a displacement.

It is not our goal to make every reader a physicist, only to remind ourselves that there are no perpetual motion machines. A good design must never violate the physical laws. Let us note some areas of sustainability that are heavily dependent on physics. First, energy is often described as a system's capacity to do work, so getting things done in the environment is really an expression of how efficiently energy is transformed from one form to another. Energy and matter relationships determine how things move in the environment. The physical movement of contaminants follows the laws of physics. For example, after a contaminant is released, physical processes go to work on transporting the contaminant and allow for *receptors* (e.g., people, ecosystems) to be exposed. The same is true for any substance, such as essential nutrients. *Transport* is one of two processes (the other is *transformation*) that determine a contaminant's or nutrient's *fate* in the environment.

Applications of Physics in Green Engineering

With the introduction of the physical laws, we can go a step further to discuss physical relationships that bear on green engineering. We begin by revisiting matter and energy. Every crucial environmental issue or problem can be represented, explained, and resolved using energy and matter fundamentals. How contaminants are formed, how they change and move through the environment, the diseases and problems they cause, and the types of treatment technologies needed to eliminate them or reduce the exposure of people and ecosystems can be seen through the prisms of energy and matter.

The relationship between energy and matter has only recently been characterized scientifically. Most simply, *energy* is the ability to do work; and *work* involves motion. *Kinetic energy* is energy due to motion. The kinetic energy of a mass m moving with velocity v is

$$E_{\text{kinetic}} = \tfrac{1}{2} m v^2 \tag{2.1}$$

Energy is also defined as the ability to cause change. Energy has a positional aspect; that is, *potential energy* is the energy resulting from one body with respect to another body. The potential energy of a mass m that is raised through a distance h is

$$E_{\text{potential}} = mgh \tag{2.2}$$

where g is the acceleration due to gravity.

Matter is anything that has both mass and volume. Matter is found in three basic *phases*: solids, liquids, and gases. The phases are very important for environmental science and engineering. The same substance in one phase may be relatively "safe," but in another phase, very hazardous. For example, a highly toxic compound may be much more manageable in the solid and liquid phases than it is in the gas phases, particularly if the most dangerous route of exposure is via inhalation. Within the same phase, solid and liquid aerosols are more of a problem when they are very small than when they are large because larger particles settle out earlier than do lighter particles, and small particles may penetrate airways more efficiently than do coarse particles.

Mass and Work

We have been using the term *mass* but have yet to define it formally. Mass is the property of matter that is an expression of matter's inertia (recall Newton's first law). So now we can also define energy. The capacity of a mass to do work is known as the *energy* of the mass. This energy may be stored or it may be released. The energy may be mechanical, electrical, thermal, nuclear, or magnetic. The first four types have obvious importance to green engineering. The movement of fluids as they carry pollutants is an example of *mechanical energy*. *Electrical energy* is applied in many treatment technologies, such as electrostatic precipitation, which changes the charge of particles in stack gases so that they may be collected rather than being released to the atmosphere. *Thermal energy* is important for heating and cooling systems, waste incineration, and sludge treatment processes. *Nuclear energy* is converted to heat that is used to form steam and turn a turbine, by which mechanical energy is converted to electrical energy. The environmental problems and challenges associated with these energy conversions include heat transfer, release of radiation, and long half-lives of certain isotopes that are formed from fission. Even the fifth form, *magnetic energy*, has importance to environmental measurements in its application to gauges and meters.

Energy is a scalar quantity. That is, it is quantified by a single magnitude. As mentioned, this contrasts with a vector quantity, which has both magnitude and direction, and which we discuss in some detail shortly. Although energy is a positive scalar quantity, a change in energy may be either positive or negative. A body's total energy can be ascertained from its mass m and its *specific energy* (i.e., the amount of energy per unit mass). The *law of conservation of energy* states that energy cannot be created or destroyed, but it may be converted among its different forms. So, in the environment, we often see the conversion of mechanical energy into electrical energy (e.g., a turbine), some of which in turn is converted to heat (hence, the need for cooling before makeup water from a turbine). The key of the law is that the sum of all forms of energy remains constant:

$$\sum E = \text{constant} \tag{2.3}$$

At this point, we should define what we mean by work. *Work* (W) is the act of changing the energy of a system or a body. An external force does external work; internal work is done by an internal force. Work is positive when the force is acting in the direction of a motion, helping to move a body from one location to another, and work is negative when the force acts in the opposite direction (e.g., friction can only do negative work in a system).

Sidebar: Applying the Synthovation/Regenerative Model: Electromagnetic Radiation

Heat and light are major concerns for design. The design of buildings is all about the right amount of each. Also devices such as computers and medical implants must dissipate heat without harming the patient. At the planetary scale, the greenhouse effect involves conversion of light to heat. To the physicist, heat and light are forms of electromagnetic radiation (EMR), which comprises wave functions that are propagated by simultaneous periodic variations in electrical and magnetic field intensities (see Fig. S2.1).

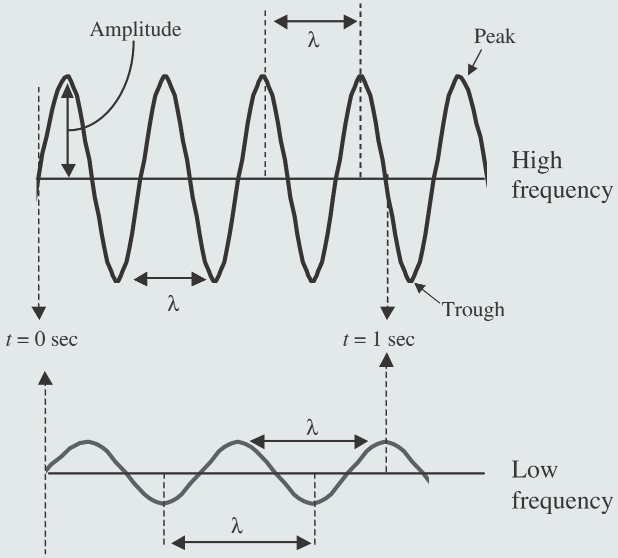


Figure S2.1 Electromagnetic radiation. The amplitude of the wave in the top chart is higher than that in lower chart. The bottom wave is 2.5 cps (2.5 Hz). The top wave is 3.5 Hz, so the bottom wave has a frequency that is 1 Hz lower than that of the top wave.

Natural and many anthropogenic sources produce EMR energy in the form of waves, which are oscillating energy fields that can interact with an organism's cells. The waves are described according to their wavelength and frequency and the energy they produce. *Wave frequency* is the number of oscillations that pass a fixed point per unit of time, measured in cycles per second (cps) [1 cps = 1 hertz (Hz)]. Thus, the shorter the wavelength, the higher the frequency. For example, the middle of the amplitude-modulated (AM) radio broadcast band has a frequency of 1 million hertz (1 MHz) and a wavelength of about 300 m. Microwave ovens use a frequency of about 2.5 billion hertz (2.5 GHz) and a wavelength of 12 cm. So the microwave, with its shorter wavelength, has a much higher frequency.

An EMR wave is made of tiny packets of energy called *photons*. The energy in each photon is directly proportional to the frequency of the wave. So the higher the frequency, the more energy there will be in each photon. Cellular material is affected in part by the intensity of the field and partly by the quantity of energy in each photon. At low frequencies EMR waves are known as *electromagnetic fields*, and at high frequencies EMR waves are referred to as *electromagnetic radiations*. Also, the frequency and energy determine whether an EMR will be ionizing or nonionizing radiation. Ionizing radiation consists of high-frequency electromagnetic waves (e.g., x-rays and gamma rays) having sufficient photon energy to produce ionization (producing positive and negative electrically charged atoms or parts of molecules) by breaking bonds of molecules. The general term *nonionizing radiation* is the portion of the electromagnetic spectrum where photon energies are not strong enough to break atomic bonds. This segment of the spectrum includes ultraviolet (UV) radiation, visible light, infrared radiation, radio waves, and microwaves, along with static electrical and magnetic fields. Even at high intensities, nonionizing radiation cannot ionize atoms in biological systems, but such radiation has been associated with other effects, such as cellular heating, changes in chemical reactions and rates, and the induction of electrical currents within and between cells.

EMR is an enigma. At certain wavelengths and frequencies it is beneficial (warmth and light), but at other wavelengths and frequencies it causes harm to an organism. A mammal may respond to EMR by increasing blood flow in the skin in response to slightly greater heating from the sun. EMR may also induce other positive health effects, such as the sun's role in helping the body produce vitamin D. Unfortunately, certain direct or indirect responses to EMR may lead to adverse effects, including skin cancer.

The data supporting UV radiation as a contaminant are stronger than those associated with the more subtle fears that sources such as high-energy power transmission lines and cell phones may be producing health effects. The World

Health Organization (WHO) is addressing the health concerns raised about exposure to radio-frequency (RF) and microwave fields, intermediate frequencies (IFs), extremely low frequency fields, and static electric and magnetic fields. Intermediate and radio-frequency fields produce heating and the induction of electrical currents, so it is highly plausible that this is occurring to some extent in cells exposed to IF and RF fields. Fields at frequencies above about 1 MHz primarily cause heating by transporting ions and water molecules through a medium. Even very low energy levels generate a small amount of heat, but this heat is carried away by the body's normal thermoregulatory processes. However, some studies indicate that exposure to fields too weak to cause heating may still produce adverse health consequences, including cancer and neurological disorders (e.g., memory loss).

HEAT ISLANDS

At the building and community scale, sites are developed and paved. This changes the color and absorbing behavior of a surface, inducing a *heat island*, which results from the thermal gradient between the developed (warmer) and undeveloped (cooler) areas (see Fig. S2.2). The surface changes increase

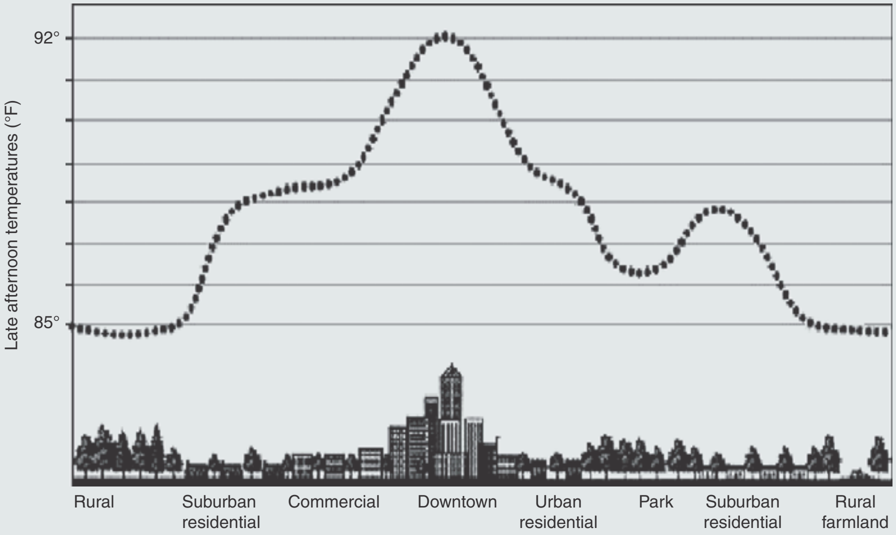


Figure S2.2 Heat island effect.

Courtesy of Heat Island Group, Lawrence Berkeley National Laboratory.

the temperature in urban areas by more than 10°F compared to surrounding undeveloped areas. Strategies against the effect include the use of shade and high-albedo (i.e., highly reflective) materials. It is also preferable that these materials, especially on roofs, have a relatively high emissivity value (i.e., the rate at which absorbed energy is radiated away from an object (see Table S2.1). Thus, the choice of building materials, roofing materials, ground cover, urban forests, planted medians, and other strategies can reduce the heat island effect and reduce the number of cooling degree-days, which translates to less energy use required to maintain thermal comfort inside buildings. It can also flatten the peak demand for electricity, so that power plants can run more efficiently.

Table S2.1 Albedo and Emissivity of Various Building Materials

Material	Albedo	Emissivity
Concrete	0.3	0.94
Tar paper	0.05	0.93
Bright galvanized iron	0.35	0.13
Bright aluminum	0.85	0.04
Aluminum paint	0.80	0.27–0.67
White single-ply roofing	0.78	0.90
Black EPDM roofing	0.045	0.88
Gravel	0.72	0.28

Source: James I. Seeley, "The protocols of white roofing," *The Concrete Specifier*, November 1997.

LIGHT POLLUTION AND TRESPASS

Light pollution and light trespassing is another EMR factor important to the consideration of development and site selection because of their negative impact on nocturnal life. Urban, suburban, and even rural areas are not nearly as dark as decades ago, due to the diffusion of light. Poor choices of lighting systems include those that distribute light waves upwardly. Better choices are those that target more intensely areas needing light (e.g., safe corridors in parking lots, parks, other public places).

Electromagnetic radiation is discussed further in Chapter 7.

Returning to potential energy and kinetic energy, potential energy is lost when the elevation of a body is decreased. The lost potential energy is usually converted to kinetic energy. If friction and other nonconservative forces are absent, the change in potential energy of a body is equal to the work needed to change the elevation of the body:

$$W = \Delta E_{\text{potential}} \tag{2.4}$$

The *work–energy principle* states that in keeping with the conservation law (recall the first law of thermodynamics), external work that is performed on a system will go into changing the system's total energy:

$$W = \Delta E = E_2 - E_1 \tag{2.5}$$

This principle is generally limited to mechanical energy relationships.

We can see these mass–energy–work relationships in solving a few example problems.

Green Physics Example 1 Calculate the work done by 4 million kilograms of effluent pumped from a sluice gate into a holding pond if the water starts from rest, accelerates uniformly to a constant stream velocity of 1 m s^{-1}, then decelerates uniformly to stop 2 m higher than the initial position in the sluice. Neglect friction and other losses.

Solution Applying the work–energy principle, the work done on the effluent is equal to the change in the effluent's energy. Since the initial and final kinetic energy is zero (i.e., the effluent starts at rest and stops again), the only change in mechanical energy is the change in potential energy. Using the initial elevation of the effluent as the reference height (i.e., $h_1 = 0$), then

$$\begin{aligned} W &= E_{2\text{potential}} - E_{1\text{potential}} = mg(h_2 - h_1) = (4 \times 10^6)(9.81\,\text{m}\,\text{s}^{-2})(2\,\text{m}) \\ &= 7.85 \times 10^7\,\text{J} \end{aligned}$$

Converting one energy form to another is in keeping with the conservation law. Most conversions are actually special cases of the work–energy principle. If a falling body is acted on by gravity, for example, the conversion of potential energy into kinetic energy is really just a way of equating the work done by the gravitational force (constant) to the change in kinetic energy. *Joule's law* states that one energy form can be converted to another energy form without loss. Regarding thermodynamic applications, Joule's law says that the internal energy of an ideal[1] gas is a function of the temperature change, not of the change in volume.

Green Physics Example 2

(a) An aerosol weighing 2 μg is emitted from a stack straight up into the atmosphere with an initial velocity of 5 m s^{-1}. Calculate the kinetic energy immediately following the stack emission. Ignore air friction and external forces (e.g., winds).

Solution From equation (2.1) we can calculate the kinetic energy:

$$E_{\text{kinetic}} = \frac{1}{2}mv^2 = \frac{1}{2}(2 \times 10^{-9}\,\text{kg})(5\,\text{m}\,\text{s}^{-1})^2 = 5 \times 10^{-7}\,\text{kg}\,\text{m}^2\,\text{s}^{-2}$$

(b) What are the kinetic energy and potential energy at the maximum height for this example?

Solution Wherever we find the point of maximum height, by definition the velocity is zero, so a close look at equation (2.1) shows that the kinetic energy must also be zero. By definition, at the maximum height, all the kinetic energy has been converted to potential energy. So the value found earlier for the kinetic energy immediately after the emission is now the value for the potential energy of the system: that is, 5×10^{-7} kg m^2 s^{-2}.

(c) What is the total energy in this example at the elevation where the particle velocity has fallen to 0.5 m s^{-1}?

Solution Even though some (even most) of the kinetic energy has been converted to potential energy, the total energy of the system remains at 5×10^{-7} kg m^2 s^{-2}.

Sidebar: Applying the Synthovation/Regenerative Model: Gestalt Thinking

Pax Scientific in San Rafael, California is leveraging lessons from the spiral flow of water and air in nature to create innovative fans and impellers that are more energy efficient. Jay Harman of Pax has discovered "streamlining principles" based on his observation of the twisted spiral form of seashells, eddies in a stream, and spiral galaxies. The similarities suggested to Harmon that these patterns were representative of the geometric fundamentals of motion.

The understanding and application of this geometry has led to the basic shapes of impellers, pumps, and fans, which are 30% more efficient in their energy use in terms of producing less heat and noise than traditional designs. Pax is now in the process of extending the application to the automotive industry as well as the commercial heating and cooling industry and licensing the technology for use in cooling fans for devices as diverse as refrigerators and personal computers. Harmon argues that biomimicry is a "Gestalt shift of humanity."

Gestalt does not translate well from German, but reflects that there is a dynamic beyond the sum of the parts. In fact, humanity itself is a community beyond adding the individual contributions of each member. It seems that early in the twentieth century, psychologists were suffering from many of the same problems as those of designers. In particular, they understood that human beings are more than the sum of their actions but the contemporary models did not allow for such synergy. Behaviorists such as John Broadus Watson treated human beings as a set of reactions to various stimuli in the environment, whereas Gestalt psychologists saw people as much more than that. Humans are integrated wholes, more than can be characterized by analyzing the parts. Thus, Harmon argues that by looking "at what nature can do and reproducing it faithfully, . . . we can solve just about any problem on earth."

Power and Efficiency

The amount of work done per unit time is *power* (P). Like energy, power is a scalar quantity:

$$P = \frac{W}{\Delta t} \tag{2.6}$$

Power can also be expressed as a function of force and velocity:

$$P = Fv \tag{2.7}$$

Time for a few more problems:

Green Physics Example 3 Oxides of nitrogen (NO_x) are air pollutants. Some of these compounds cause diseases, but they are also important because they are part of the chemical reaction that leads to the formation of ozone, which causes lung problems and is a key ingredient of summertime smog in the lower troposphere.

(a) The emission of NO_x from an older car's exhaust is 100 mg per kilometer traveled. If this increases by 10 mg km^{-1} for each additional horsepower expended, how much additional NO_x would be released if the car traveling 100 km h^{-1} supplies a constant horizontal force of 50 newtons (N) to carry a trailer?

Solution First, we must calculate the tractive power (hp) required to tow the trailer using equation (2.7):

$$\begin{aligned} P &= Fv \\ &= [(50\,\mathrm{N})(100\,\mathrm{km\,h^{-1}})(1000\,\mathrm{m\,km^{-1}})] \\ &\quad \times [(60\,\mathrm{s\,min^{-1}})(60\,\mathrm{min\,h^{-1}})(1000\,\mathrm{W\,kW^{-1}})]^{-1} \\ &= 1.389\,\mathrm{kW} \end{aligned}$$

1 hp = 0.7457 kW, so $P = 1.86$ hp. Therefore, towing the trailer at this speed adds 1.86×10 mg, or 18.6 mg of NO_x to the atmosphere for each kilometer traveled. This means that at 100 km h^{-1}, the old car is releasing 118.6 mg NO_x for each kilometer it travels. Indeed, a common challenge to green engineering is that waste (e.g. NO_x emissions) accompanies commensurately increased energy demand. The good news is that reducing waste can have the added bonus of decreased energy demand.

(b) How much can we lower the NO_x emitted if the old car above produces 90 mg of NO_x for each mile traveled 50 km h^{-1} and the NO_x increase from towing falls to 5 mg km^{-1} for each horsepower expended?

Solution Once again, we use equation (2.7):

$$\begin{aligned} P &= Fv \\ &= [(50\,\mathrm{N})(50\,\mathrm{km\,h^{-1}})(1000\,\mathrm{m\,km^{-1}})] \\ &\quad \times [(60\,\mathrm{s\,min^{-1}})(60\,\mathrm{min\,h^{-1}})(1000\,\mathrm{W\,kW^{-1}})]^{-1} \\ &= 0.695\,\mathrm{kW} \\ &= 0.93\,\mathrm{hp} \end{aligned}$$

Therefore, towing the trailer at this speed adds 0.93×5 mg, or 4.7 mg of NO_x to the atmosphere for each kilometer traveled. This means that at 50 km h^{-1}, the old car is releasing $90 + 4.7 = 94.7$ mg of NO_x for each kilometer it travels. So, by slowing down, the NO_x emissions drop 23.9 mg for each kilometer traveled.

These examples illustrate that changing even one variable, such as vehicle weight, can substantially improve energy efficiency and environmental quality. That is, when the energy efficiency improved, fewer pollutants (i.e., NO_x) are released. This demonstrates that pollution is actually a measurement of inefficiency.

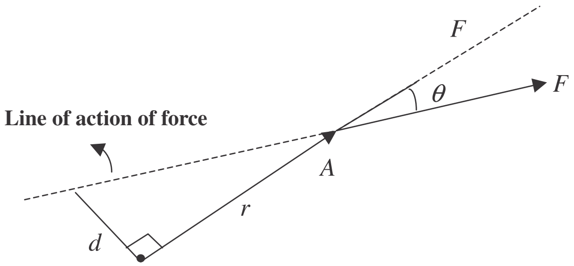


Figure 2.5 Moment about a single force.

MORE ABOUT FORCES

Force is crucial to green engineering. An integrated design strategy must account for all forces. So let us consider briefly the various types of forces. A point force (or concentrated force) is a vector with magnitude, direction, and location. The force's line of action is the line in the direction of force that is extended forward and backward.

Another aspect of force is the *moment*, which is the tendency of a force to rotate, twist, or turn a rigid body around a pivot. In other words, when a body is acted on by a moment, the body will rotate. But even if the body does not actually rotate because it is being restrained, the moment still exists. So the units of a moment are length × force (e.g., N·m). The moment is zero when the line of action of the force passes through the center of rotation (pivot). A moment important to green engineering is the moment of force about a line. A pump, for example, has a fixed rotational axis. This means that it turns around a line, not about a pivot. The moment about a single force in shown in Figure 2.5. The moment M of a force F about point A in the figure is the product of the force and the perpendicular distance d from that point to the line of action for the force. So the magnitude of this moment is

$$M_{\mathrm{A}} = Fd \tag{2.8}$$

Sidebar: Applying the Synthovation/Regenerative Model: Beyond Waldon Pond

> As to methods there may be a million and then some, but principles are few. The man who grasps principles can successfully select his own methods. The man who tries methods, ignoring principles, is sure to have troubles.
>
> Ralph Waldo Emerson

In Chapter 1 we discussed the fact that although wind energy is renewable, if not designed properly, its use may still be inefficient. It is commendable to add wind energy systems to a building, but it is best to design these systems into the building design process. For example, the building form, sunlight exposure, siting, and local climate are factors that if considered collectively, can mean the difference between a green versus a less than optimal system. This does not mean that either the conventional design of a building or that of an added system (e.g., a windmill) drives the other. In fact, the beauty of an integrated system is that the two systems are merged and that all energy system options are assessed very early with regard to function. Shelter, energy, exposure, materials, heat and air exchanges, and every aspect of a building system are considered together.

The Pearl River Tower, designed by the architectural engineering firm Skidmore, Owings & Merrill's Chicago office, is now under construction in Guangzhou, China (see Figs. S2.3 and S2.4). The design solution for this zero-energy high-rise building integrates wind-harvesting turbines into the form of the building, with two large intakes carefully engineered and sculpted into the building's façade. The forms are designed and tuned to allow wind to pass

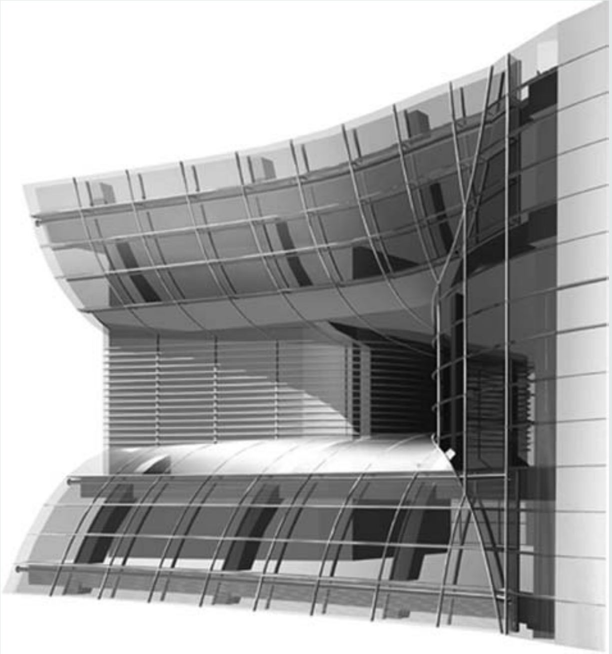


Figure S2.3 Intake at turbines for Pearl River Tower.

Courtesy of Skidmore, Owings, & Merrill, LLP.

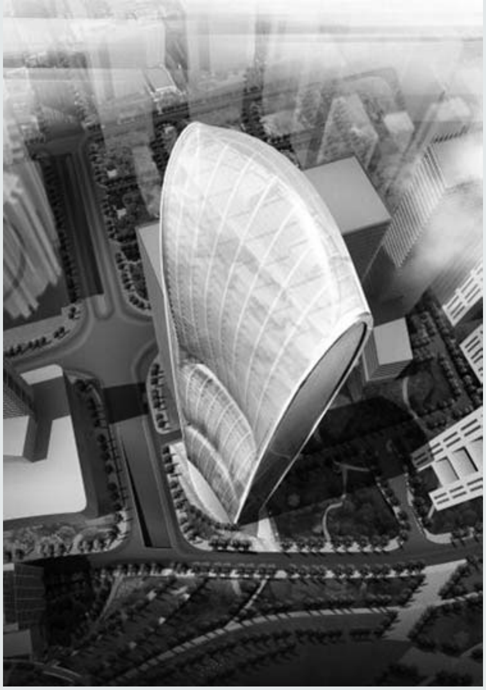


Figure S2.4 Pearl River Tower rendering.

Courtesy of Skidmore, Owings, & Merrill, LLP.

through the building and turn the wind turbines with the greatest efficiency by minimizing turbulence and restriction of flow much as a turbocharger on a car improves performance. In this case it is estimated that the improved performance generated by the increased wind velocity as it enters the turbines will result in up to 15 times more electricity generated than that from a stand-alone wind generator. Generating energy on-site where it will be consumed also overcomes the significant loss of energy that occurs in transmission. Recall that the second law of thermdynamics holds that any conversion of energy results in an increase in entropy. That is, an isolated system's energy becomes less available to do work. In addition to the solution's consideration of airflow to generate a portion of the building's power needs, the solution responds to the specifics of place by orienting the building to an adjoining park and to take advantage of prevailing winds unlikely to be interrupted by future tower development. The design for the passage of wind through a building also yields structural advantages, as it is anticipated that the openings will help reduce the building's sway.

The design reality of Emerson's quote is: Form truly follows function.

A *couple* is formed by two equal and parallel forces that have noncollinear lines of actions that are opposite in sense. The moment of a couple is determined from the product of the force and the minimum distance between the two forces. Like the moment in a point of space, the equation for the moment of a couple is $M = Fd$. Thus, couples are common in all mechanical devices, including windmills, pumps, and engines.

Environmental Dynamics

Dynamics is the general area of physics concerned with moving objects. It includes kinematics and kinetics. *Kinematics* is concerned with the study of a body in motion independent of forces acting on the body. That is, kinematics is the branch of mechanics concerned with the motion of bodies with reference to force or mass. This is accomplished by studying the geometry of motion irrespective of what is causing the motion. Therefore, kinematics relates position, velocity, acceleration, and time.

Hydrodynamics is the important branch of environmental mechanics that is concerned with deformable bodies. It is concerned with the motion of fluids. Therefore, it is an important underlying aspect of contaminant transport and movements of fluids, and considers fluid properties such as compressibility and viscosity. These are key to understanding water distribution and treatment systems, flows in pipes, and the design of pumps and fluid exchange systems.

Kinetics is the study of motion and the forces that cause motion. This includes analyzing force and mass as they relate to translational motion. Kinetics also considers the relationship between torque and moment of inertia for rotational motion.

A key concept for environmental dynamics is that of *linear momentum*, which is the product of mass and velocity. A body's momentum is conserved unless an external force acts on a body. Kinetics is based on Newton's *first law of motion*, which states that a body will remain in a state of rest or will continue to move with constant velocity unless an unbalanced external force acts on it. Stated as the *law of conservation of momentum*, linear momentum is unchanged if no unbalanced forces act on a body. Or, if the resultant external force acting on a body is zero, the linear momentum of the body is constant.

Kinetics is also based on Newton's *second law of motion*, which states that the acceleration of a body is directly proportional to the force acting on that body and inversely proportional to the body's mass. The direction of acceleration is the same as the force of direction. The equation for the second law is

$$\mathbf{F} = \frac{d\mathbf{p}}{dt} \tag{2.9}$$

where $\mathbf{p}$ is the momentum.

Recall that Newton's *third law of motion* states that for every acting force between two bodies, there is an equal but opposite reacting force on the same line of action. The equation for this law is

$$\mathbf{F}_{\text{reacting}} = -\mathbf{F}_{\text{acting}} \tag{2.10}$$

As mentioned, a force that is particularly important to green systems is *friction*, which is a force that always resists motion or impending motion. Friction acts parallel to the contacting surfaces. When bodies come into contact with one another, friction acts in the direction opposite that which is bringing the objects into contact.

Fluids

Green engineers are keenly interested in fluids. The obvious fluids that are important at all scales, from molecular to global, are water and air. To identify a hazard associated with the chemical, or to take advantage of a fluid in a design the fluid properties must be understood. For example, if a contaminant's fluid properties make it insoluble in water and blood, the target tissues are more likely to be lipids. If a chemical is easily absorbed, the hazard may be higher. However, if it does not change phases under certain cellular conditions, it could be more or less toxic, depending on the organ.

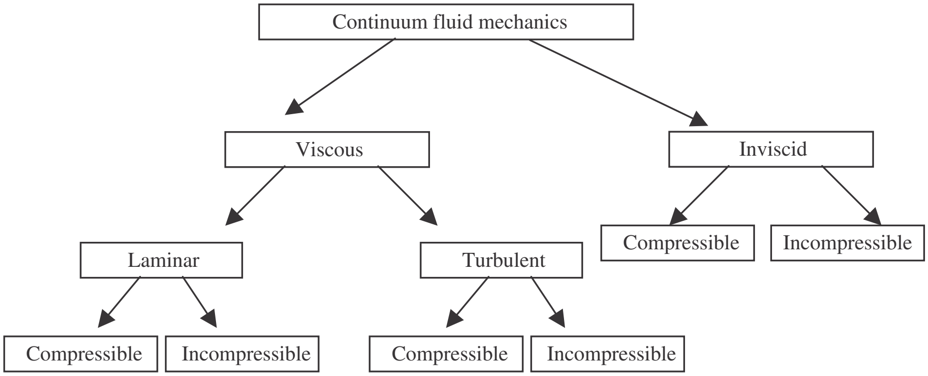
The fluid properties of an agent, whether chemical or biological (e.g., mold and pollen), help us to determine if the contaminant is likely to be found in the environment (e.g., in the air as a vapor, sorbed to a particle, dissolved in water, or taken up by biota). Likewise, if a fluid is easily compressible if may be useful in cooling systems.

Physical transport is a function of the mechanics of fluids, but it is also a chemical process, such as when and under what conditions transport and chemical transformation processes become steady state or nearly steady state (e.g., sequestration and storage in the environment). Thus, transport and transformation of contaminants and nutrients depend on the characteristics of fluids.

A *fluid* is a collective term that includes all liquids and gases.[2] A *liquid* is matter that is composed of molecules that move freely among themselves without separating from each other. A *gas* is matter composed of molecules that move freely and are infinitely able to occupy the space with which they are contained at a constant temperature. Engineers define a fluid as a substance that will deform continuously upon the application of a shear stress (i.e., a stress in which the material on one side of a surface pushes on the material on the other side of the surface with a force parallel to the surface).

Figure 2.6 Classification of fluids based on continuum fluid mechanics.

Adapted from Research and Education Association, *The Essentials of Fluid Mechanics and Dynamics I*, REA, Piscataway, NJ, 1987.



Fluids can be classified according to observable physical characteristics of flow fields. A continuum fluids mechanics classification is shown in Figure 2.6. *Laminar flow* is in layers, whereas *turbulent flow* has random movements of fluid particles in all directions. In *incompressible flow*, the variations in density are assumed to be constant, whereas *compressible flow* has density variations, which must be included in flow calculations. *Viscous flows* must account for viscosity, whereas inviscid flows assume that the viscosity is zero.

The *time rate of change* of a fluid particle's position in space is the fluid velocity $\mathbf{V}$. This is a vector field quantity. Speed V is the magnitude of the vector velocity $\mathbf{V}$ at some given point in the fluid, and average speed $\bar{V}$ is the mean fluid speed through a control volume's surface. Therefore, velocity is a *vector quantity* (magnitude and direction), whereas speed is a *scalar quantity* (magnitude only). The standard units of velocity and speed are meters per second ($\mathrm{m\ s^{-1}}$).

Velocity is important when determining pollution, such as mixing rates after an effluent is discharged to a stream, how rapidly an aquifer will become contaminated, and the ability of liners to slow the movement of leachate from a landfill toward the groundwater. The distinction between velocity and speed is seldom made, even in technical discussion. Surface water flow, known as *stream discharge* Q, has units of volume per time. Although the appropriate units are $\mathrm{m^3\ s^{-1}}$, most stream discharge data in the United States are reported as the number of cubic feet of water flowing past a point each second (cfs). Discharge is derived by measuring a stream's velocity at numerous points across the stream. Since heights (and volume of water) in a stream change with meteorological and other conditions, stream-stage/stream-discharge relationships are found by measuring stream discharge during different stream stages. The flow of a stream is estimated based on many measurements. The mean of the flow measurements at all stage heights is reported as the estimated discharge. The calculation of discharge[3] of a stream of width w_s is the sum of the products of mean depth, mean width, and mean velocity:

$$Q = \sum_{n=1}^{n} \frac{1}{2}(h_n + h_n - 1)(w_n + w_n - 1) \times \frac{1}{2}(v_n + v_n - 1)\frac{1}{2}(h_n + h_{n-1}) \tag{2.11}$$

where

Q = discharge ($\mathrm{m^3\ s^{-1}}$)
h_n = nth water depth (m)
w_n = nth distance from baseline or initial point of measurement (m)
v_n = nth velocity ($\mathrm{m\ s^{-1}}$) from velocity meter

Another important fluid property is *pressure*. A force per unit area is pressure:

$$p = \frac{F}{A} \tag{2.12}$$

So p is a type of stress that is exerted uniformly in all directions. It is common to use pressure instead of force to describe the factors that influence the behavior of fluids. The standard unit of p is the pascal (P), which is equal to 1 N $\mathrm{m^{-2}}$. The preferred pressure unit in this book is the kilopascal (kP), since the standard metric unit of pressure is the pascal, which is quite small.

Potential and kinetic energy discussions must consider the fluid acceleration due to gravity. In many ways, it seems that acceleration was a major reason for Isaac Newton's need to develop the calculus.[4] Known as the *mathematics of change*, calculus is the mathematical means of describing acceleration and addressed Newton's need to express mathematically his new law of motion. *Acceleration* is the time rate of change in the velocity of a fluid particle. In terms of calculus, it is a second derivative. That is, it is the derivative of the velocity function—and a derivative of a function is itself a function, giving its rate of change. This explains why the second derivative must be a function showing the rate of change of the rate of change, which is readily apparent from the units of acceleration: length per time per time ($\mathrm{m\ s^{-2}}$).

The relationship between mass and volume is important in both environmental physics and chemistry and is a fundamental property of fluids. The *density* ρ of a fluid is defined as its mass per unit volume. Its metric units are kg $\mathrm{m^{-3}}$. The density of an ideal gas is found using the specific gas constant and applying the *ideal gas law:*

$$\rho = p(RT)^{-1} \tag{2.13}$$

where

p = gas pressure
R = specific gas constant
T = absolute temperature

The specific gas constant must be known to calculate gas density. For example, the R value for air is 287 J kg^{-1} K^{-1}. The specific gas constant for methane (R_{CH4}) is 518 J kg^{-1} K^{-1}.

Density is a very important fluid property in green design and operations. For example, a first responder must know the density of substances in an emergency situation. If a substance is burning, whether it is of greater or lesser density than water will be one of the factors in determining how to extinguish the fire. If the substance is less dense than water, the water will probably settle below the layer of water, making water a poor choice for fighting the fire. So any flammable substance whose density is less than that of water (see Table 2.2), such

Table 2.2 Densities of Some Important Environmental Fluids

Fluid	Density (kg m^{-3}) at 20°C (unless otherwise noted)
Air at standard temperature and pressure (STP) = 0°C and 101.3 N m^{-2}	1.29
Air at 21°C	1.20
Ammonia	602
Gasoline	700
Diethyl ether	740
Ethanol	790
Acetone	791
Kerosene	820
Turpentine	870
Benzene	879
Pure water	1,000
Seawater	1,025
Carbon disulfide	1,274
Chloroform	1,489
Tetrachloromethane (carbon tetrachloride)	1,595
Lead	11,340
Mercury	13,600

Table 2.3 Composition of Fresh Waters (River) and Marine Waters for Some Important Ions

Composition	River Water	Salt Water
pH	6–8	8
Ca^{2+}	4×10^{-5} M	1×10^{-2} M
Cl^-	2×10^{-4} M	6×10^{-1} M
HCO_3^-	1×10^{-4} M	2×10^{-3} M
K^+	6×10^{-5} M	1×10^{-2} M
Mg^{2+}	2×10^{-4} M	5×10^{-2} M
Na^+	4×10^{-4} M	5×10^{-1} M
SO_4^{2-}	1×10^{-4} M	3×10^{-2} M

Source: K. A. Hunter, J. P. Kim, and M. R. Reid, "Factors influencing the inorganic speciation of trace metal cations in freshwaters," *Marine Freshwater Research*, 50, 367–372, 1999; R. R. Schwarzenbach, P. M. Gschwend, and D. M. Imboden, *Environmental Organic Chemistry*, Wiley-Interscience, New York, 1993.

as benzene or acetone, will require fire-extinguishing substances other than water. For substances heavier than water, such as carbon disulfide, water may be a good choice. Thus, a good green design properly segregates and labels materials based in part on their densities.

Another important comparison in Table 2.2 is that of pure water and seawater. The density difference between these two water types is important for marine and estuarine ecosystems. Salt water contains a significantly greater mass of ions than that in fresh water (see Table 2.3). The denser saline water can wedge beneath fresh waters and pollute surface waters and groundwater (see Fig. 2.7). This phenomenon, known as *saltwater intrusion*, can significantly alter an ecosystem's structure and function and threaten freshwater organisms. It can also pose a huge challenge to coastal communities that depend on aquifers for their water supply. Part of the problem and the solution to the problem can be found in dealing with the density differentials between fresh and saline waters. Thus, fluid density is a constraint in green design.

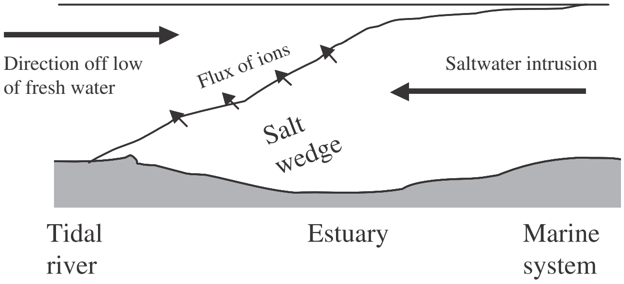


Figure 2.7 Saltwater intrusion into a freshwater system. The denser salt water is submerged under the lighter freshwater system. The same phenomenon can occur in coastal aquifers.

Sidebar: Applying the Synthovation/Regenerative Model: The Bird Nest

Structure influences forces. As mentioned in Chapter 1, buildings can be viewed much like an organism. The building grows from a small idea. Its shape and size must meet certain functional expectations and all the organs, bones, skins, and so on, must be integrated and grow mutually.

The Beijing Olympic Stadium designed for the 2008 games seeks to integrate multiple complex systems—structure, walls, roof, and ventilation—into a cohesive whole that merges function with form (see Figs. S2.5 and S2.6). The

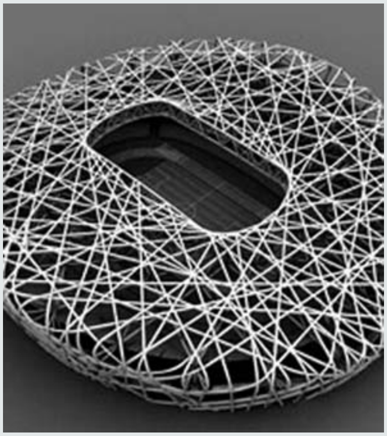


Figure S2.5 Beijing Olympic Stadium.

Courtesy of Arup.

Figure S2.6 Construction of Beijing Olympic Stadium.

Courtesy of FHKE, released under a Creative Commons Attribution-Share Alike 2.0 Generic license, http://flickr.com/photos/fhke/539799249/.

design is the result of collaboration between architects Herzog & de Meuron, ArupSport, and the China Architecture Research Group. The structure has been referred to fondly as the "bird's nest," its structure also serving as façade and morphing into roof. An innovative, inflatable "cushion" system similar to an inflatable bladder provides infill within the structure to allow the stadium to regulate the environment within the structure in response to changes in wind, weather, and solar conditions.

The reciprocal of a substance's density is known as its *specific volume* (v). This is the volume occupied by a unit mass of a fluid. The units of v are reciprocal density units ($m^3\ kg^{-1}$). Stated mathematically, this is

$$v = \rho^{-1} \tag{2.14}$$

The weight of a fluid on the basis of its volume is known as the *specific weight* (γ). Scientists and engineers sometimes use the term interchangeably with density. Geoscientists frequently refer to a substance's specific weight. A substance's γ is not an absolute fluid property because it depends on the fluid itself and the local gravitational force:

$$\gamma = gp \tag{2.15}$$

Specific weight units are the same as those for density (e.g., $kg\ m^{-3}$).

The fractional change in a fluid's volume per unit change in pressure at constant temperature is the fluid's coefficient of compressibility. Any fluid can be compressed in response to the application of pressure (p). For example, water's compressibility at 1 atm is $4.9 \times 10^{-5}\ atm^{-1}$. This compares to the lesser compressibility of mercury ($3.9 \times 10^{-6}\ atm^{-1}$) and the greater compressibility of hydrogen ($1.6 \times 10^{-3}\ atm^{-1}$). A fluid's bulk modulus E is a function of stress and strain on the fluid and is a description of its compressibility, and is defined according to the fluid volume (V):

$$E = \frac{\text{stress}}{\text{strain}} = -\frac{dp}{dV/V_1} \tag{2.16}$$

E is expressed in units of pressure (e.g., kP). Water's $E = 2.2 \times 10^6$ kP at 20°C.

Surface tension effects occur at liquid surfaces (liquid–liquid, liquid–gas, liquid–solid interfaces). Surface tension σ is the force in the liquid surface normal to a line of unit length drawn in the surface. Surface tension decreases with temperature and depends on the contact fluid. Surface tension is involved in capillary rise and drop. Water has a very high σ value (approximately $0.07\ N\ m^{-2}$ at 20°C). Of the environmental fluids, only mercury has a higher σ value (see

Table 2.4 Surface Tension (Contact with Air) of Selected Environmental Fluids

Fluid	Surface Tension σ ($\mathrm{N\ m^{-1}}$ at 20°C)
Acetone	0.0236
Benzene	0.0289
Ethanol	0.0236
Glycerin	0.0631
Kerosene	0.0260
Mercury	0.519
n-Octane	0.0270
Tetrachloromethane	0.0236
Toluene	0.0285
Water	0.0728

Table 2.4). The high surface tension creates a type of skin on a free surface, which is how an object that is denser than water (e.g., a steel needle) can "float" on a still water surface. It is the reason that insects can sit comfortably on water surfaces. Surface tension is somewhat dependent on the gas that is contacting the free surface. If not indicated, it is usually safe to assume that the gas is the air in the troposphere.

Capillarity is a particularly important fluid property of groundwater flow and the movement of contaminants above the water table. In fact, the zone immediately above the water table is called the *capillary fringe*. Regardless of how densely soil particles are arranged, void spaces (i.e., pore spaces) will exist between the particles. By definition, the pore spaces below the water table are filled exclusively with water. However, above the water table, the spaces are filled with a mixture of air and water. As shown in Figure 2.8, the spaces between unconsolidated material (e.g., gravel, sand, clay) are interconnected and behave like small conduits or pipes in their ability to distribute water. Depending on the grain size and density of packing, the conduits will vary in diameter, ranging from large pores (i.e., macropores), to medium pore sizes (i.e., mesopores), to extremely small pores (i.e., micropores).

Fluid pressures above the water table are negative with respect to atmospheric pressure, creating tension. Water rises for two reasons: its adhesion to a surface, and the cohesion of water molecules to one another. Higher relative surface tension causes a fluid to rise in a tube (or a pore) and is indirectly proportional to the diameter of the tube. In other words, capillarity increases with decreasing tube diameter (e.g., tea will rise higher in a thin straw in a glass of iced tea than in a fatter straw). The rise is limited by the weight of the fluid in the tube. The rise ($h_{\text{capillary}}$) of the fluid in a capillary is expressed as follows (Figure 2.9 gives an

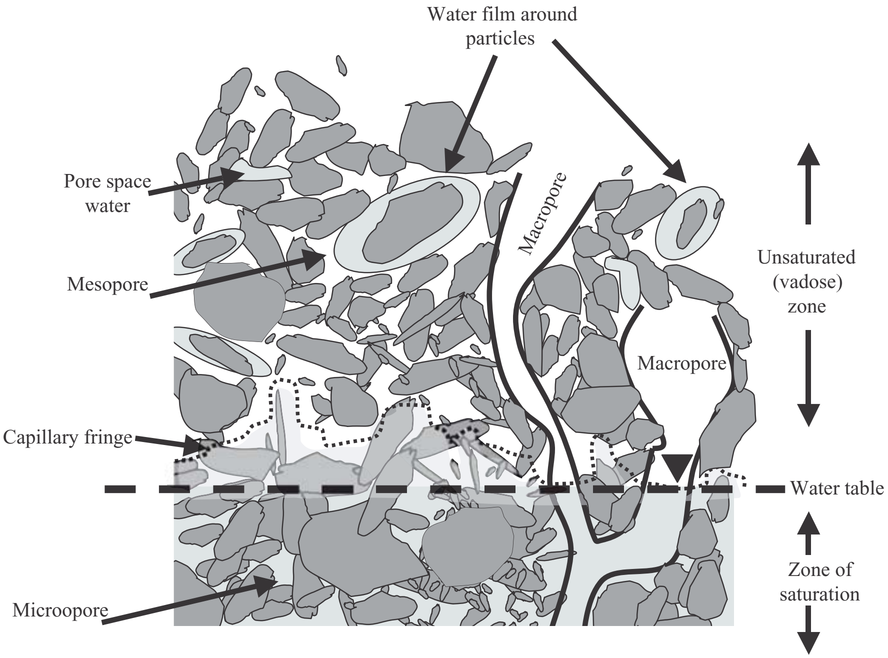


Figure 2.8 Capillarity fringe above the water table of an aquifer.

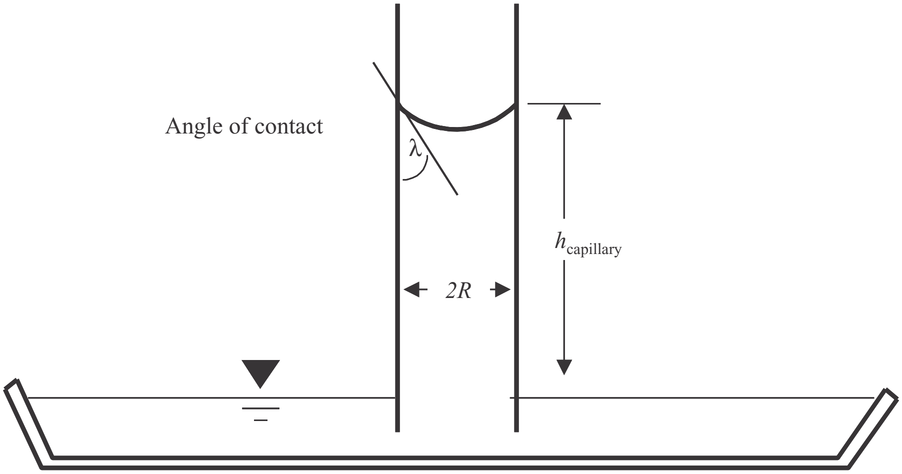


Figure 2.9 Rise of a fluid in a capillary.

example of the variables):

$$h_{\text{capillary}} = \frac{2\sigma \cos \lambda}{\rho_w g\, R} \tag{2.17}$$

where

σ = fluid surface tension (g s^{-2})
λ = angle of meniscus (concavity of fluid) in capillary (degrees)
ρ_w = fluid density (g cm^{-3})
g = gravitational acceleration (cm s^{-1})
R = radius of capillary (cm)

Capillarity and surface tension are important to green design for numerous reasons. This is one of the means by which water permeates materials, bringing with it contaminants and nutrients, such as those that cause the growth of mold and other fungi. It is also the principal means by which roots obtain nutrients. In fact, one of the growing applications of root transfer is phytoremediation of hazardous waste sites. Plant life is used to extract contaminants (e.g. heavy metals) from soil which is translocated to the stems and leaves, which are harvested and taken away. The soil grows progressively cleaner with time.

Sidebar: Applying the Synthovation/Regenerative Model: Fluids and Buildings

Fluid dynamics and pressure relationships are examples of physical factors that can make or break a green design: for example, when designing a building, a working knowledge of how temperature and other indoor and outdoor factors can greatly affect the indoor environment and create opportunities to build more efficient air-handling systems. Cooling and heating the air can be done more efficiently and effectively in achieving the objective of providing comfort for the occupants by incorporating the shape of rooms, the interrelationships of these rooms (vertically and horizontally), and air movement into the design at the outset (see Fig. S2.7). If we consider fluid dynamics early, we can control the transport mechanisms to our advantage and use less energy to temper the environment. For example, in winter, our design will use natural processes to circulate air; warm air is sent to nonliving spaces in summer and to living spaces in winter.

By applying scientific principles and understanding of the natural tendency for air to stratify in layers of various temperatures, architects and engineers are

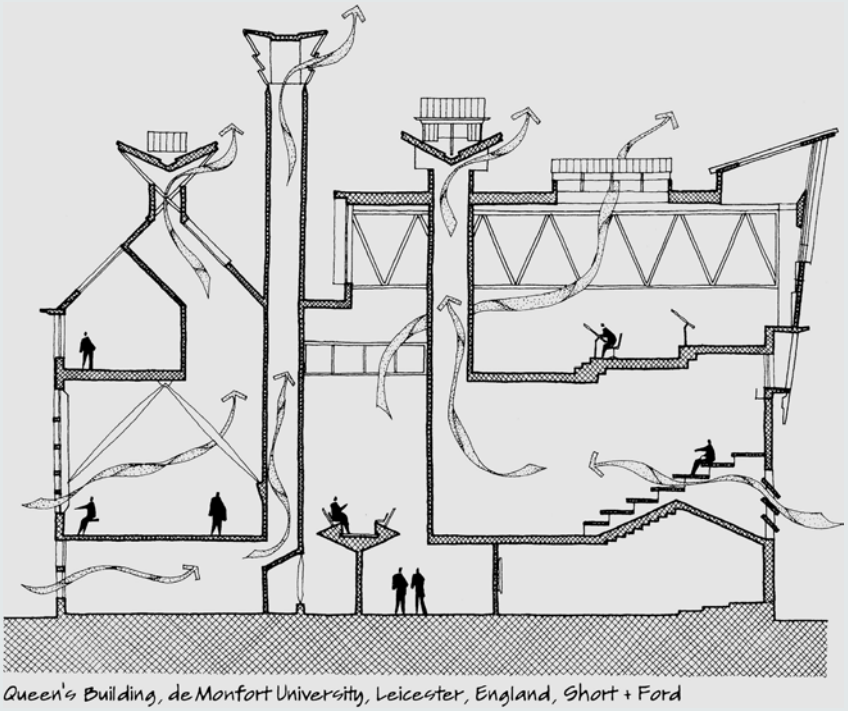


Figure S2.7 Air movement within a building.

From Brown and DeKay, *Sun, Wind and Light*, Wiley, Hoboken, NJ.

able to harness the stack and venturi effects to create negative pressure and ventilate the interior of a building without relying on mechanical means. Similar strategies are available by recognizing the thermal inertia of heavy structures and how this can be used to smooth temperature fluctuations and avoid extreme swings in temperature.

Applying principles of natural convection has also led to recent energy-saving innovations in the form of chilled beam technology (see Fig. S2.8). *Chilled beams* combine the principles of radiant cooling systems with the principles of natural convection as air from occupied areas flows into the ceiling cavity, where the air passes between the chilled beam's coils and is cooled, falling back into the occupied zone, while air that is heated rises and flows into the void created by the descending cool air. The result is improvement in comfort levels for occupants and the elimination of much of the ductwork and mechanical system equipment required above the ceiling in traditional heating, ventilating, and air-conditioning systems.

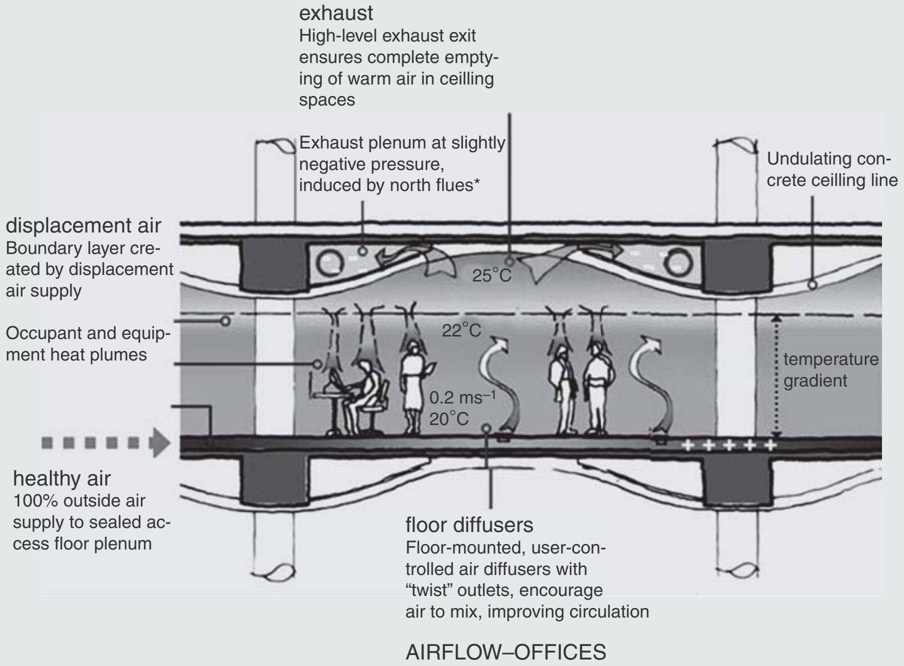


Figure S2.8 Cross section of a chilled beam used in cooling an interior office environment.

Courtesy of the city of Melbourne, Australia,
http://www.melbourne.vic.gov.au/info.cfm?top=171&pa=1943&pg=1937.

The contact angle indicates whether cohesive or adhesive forces are dominant in capillarity. When λ values are greater than 90°, cohesive forces are dominant; when $\lambda < 90^\circ$, adhesive forces dominate. Thus, λ is dependent on both the type of fluid and the surface to which it comes in contact. For example, water–glass $\lambda = 0^\circ$; ethanol–glass $\lambda = 0^\circ$; glycerin–glass $\lambda = 19^\circ$; kerosene–glass $\lambda = 26^\circ$; water–paraffin $\lambda = 107^\circ$; and mercury-glass $\lambda = 140^\circ$. At the base of the capillary fringe the soil is saturated without regard to pore size. In the vadose zone, however, the capillary rise of water will be highest in the micropores, where relative surface tension and the effects of water cohesion are greatest.

Capillarity and surface tension are important properties in nature, such as the movement of fluids in roots and leaves. As such, designers wishing to take advantage of the concepts of biomimicry introduced in Chapter 1 need to have a working knowledge of these properties.

Another property of environmental fluids is the *mole fraction*. If a composition of a fluid made up of two or more substances (A, B, C, . . .), the mole fraction (x_A, x_B, x_C, . . .) is the number of moles of each substance divided by the total number of moles for the entire fluid:

$$x_A = \frac{n_A}{n_A + n_B + n_C + \cdots} \tag{2.18}$$

The mole fraction value is always between 0 and 1. The mole fraction may be converted to mole percentage as

$$x_{A\%} = x_A \times 100 \tag{2.19}$$

For gases, the mole fraction is the same as the volumetric fraction of each gas in a mixture of more than one gas.

The amount of resistance to flow when it is acted on by an external force, especially a pressure differential or gravity, is the fluid's viscosity. This is a crucial fluid property used in numerous green engineering applications, particularly in air pollution plume characterization, sludge management, and wastewater and drinking water treatment and distribution systems.

Bernoulli's equation states that when fluid is flowing in a long, horizontal pipe with constant cross-sectional area, the pressure along the pipe must be constant. However, as the fluid moves in the pipe, there will be a pressure drop. A pressure difference is needed to push the fluid through the pipe to overcome the drag force exerted by the pipe walls on the layer of fluid that is making contact with the walls. Since the drag force exerted by each successive layer of the fluid on each adjacent layer is moving at its own velocity, a pressure difference is needed (see Fig. 2.10). The drag forces are known as *viscous forces*. Thus, the fluid velocity is not constant across the pipe's diameter, owing to the viscous forces. The greatest velocity is at the center (farthest away from the walls), and the lowest velocity is found at the walls. In fact, at the point of contact with walls, the fluid velocity is zero.

So if P_1 is the pressure at point 1 and P_2 is the pressure at point 2, with the two points separated by a distance L, the pressure drop ΔP is proportional to the flow rate:

$$\Delta P = P_1 - P_2 \tag{2.20}$$

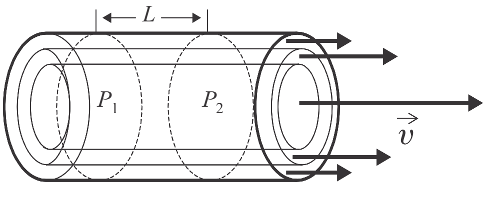


Figure 2.10 Viscous flow through a horizontal pipe. The highest velocity is at the center of the pipe. As the fluid approaches the pipe wall, the velocity approaches zero.

and

$$\Delta P = P_1 - P_2 = I_v R \tag{2.21}$$

where I_v is the volume flow rate and R is the proportionality constant, representing the resistance to the flow. R depends on the length L of the pipe section, the pipe's radius, and the fluid's viscosity.

Bioenergetics

Energy is stored and used in organisms. The manner in which energy is transfered and transformed in living organism is known as bioenergetics. The thermodynamics involved as the energy is transformed and released in the environment will determine the efficiency and health of microbes as they help us treat contaminants, how ecosystems transform the sun's energy throughout the food chain, and which chemical reactions will break down contaminants, metabolize substances, and ultimately participate in the toxicological response of organisms, including humans. In addition, bioenergetics can be a resource for energy needs in buildings and devices, such as heat produced by microbial metabolism. It is also a measure of efficiency. For example, using biomass from lower trophic states (e.g., producers) is more energy efficient than that from higher trophic states (e.g., consumers).

Systematic Design and the Status Quo

Interestingly, thermodynamic terms are frequently used in design. We must know the system, the boundary, the surroundings, the constraints, and the drivers. These must all be incorporated into the design. So the concept of systems is important in another way: It is a mental construct that influences the way that designers think. Designing to improve a process or to solve a problem requires that we keep in mind how best to measure success "systematically." The two most common design metrics are efficiency and effectiveness. The first is a thermodynamics term. The second is a design term. *Efficiency* and *effectiveness* refer to whether a design is conducive to the purpose for which it was created, and whether the design function performs some task, respectively. Unlike mathematics, engineering and architecture are not exclusively deductive endeavors. Designers also base knowledge on experience and observation. Design professions first generate rules based on observations (i.e., the laws of nature: chemistry, physics, biology, etc.) of the world around them: the way things work. Once they have this understanding, they may apply it by using the rules to create something, some technology, designed to reach some end: from keeping food cold to delivering nutrition to comatose patients. According to the National Academy of Engineering, *technology* "is the outcome of engineering; it is rare that science translates directly to technology, just as it is not true that engineering is just applied science."[5]

One of the themes of this book is the importance of innovation. The playing field is not even. The status quo often works against design and engineering programs. The "earth homes" of the 1970s had many advantages in terms of energy savings. Most of the structures of the homes (at least three walls) were often underground. Early solar panels clearly made sense in terms of alternative energy at the home scale. Windmills had the same advantage. Of course, some of the failure to entice designers, contractors, developers, and homeowners were real, such as less daylight available in earth homes, problems of cost and reliability of early versions of photovoltaic cells, and noise and other aesthetic problems with windmills. However, some of the resistance to adoption was the sheer difference between these technological advances and that which the public perceived to be "normal." Real estate agents cautioned against buildings that were too different, since this could affect the resale value. Homeowners did not want to be perceived as "flaky." So any innovation, no matter how efficient and efficacious, will often meet with resistance.

When we teach green engineering and sustainable design courses, we must keep in mind that there will be recalcitrance. This xenophobia is not limited to the less educated but exists within the design professions themselves. Green engineering and design is a paradigm shift. This phenomenon was noted in the late twentieth century by the famous philosopher of science, Thomas S. Kuhn, who applied it to scientific discovery. Kuhn changed the meaning of the word *paradigm*, extending the term to mean an accepted specific set of scientific practices. The scientific paradigm is made up of what is to be observed and analyzed, the questions that arise pertaining to this scientific subject matter, to whom such questions are to be asked, and how the results of investigations into this subject matter will be interpreted. The paradigm can be harmful if it allows incorrect theories and information to be accepted by the scientific and engineering communities. Some of the resistance against shifting paradigms results from *groupthink*.[6]

Innovations in design occur when a need or opportunity arises (hence the adage "Necessity is the mother of invention"). For example, design professionals may first develop an understanding of the thermodynamics behind a phase-change heat pump and then apply this knowledge when society experiences a *need* to keep food cold.

The idea of science of application through the dynamic form was articulated by Donald Stokes in his analysis of the post–World War II scientific research paradigm. In particular, Stokes' interest in the historical progression of the ideas of "basic" and "applied" research is quite instructive. In 1944, Vannevar Bush, Franklin D. Roosevelt's director of the wartime Office of Scientific Research and Development, was asked to consider the role of science in peacetime. He did this in his work *Science, the Endless Frontier*, through two aphorisms. The first was that "basic research is performed without thought of practical ends." According to Bush, basic research is to contribute to "general knowledge and an understanding of nature and its laws." Seeing an inevitable conflict between research to increase understanding and research geared toward use, he held that "applied research invariably drives out pure."[7]

Today, Bush's "rugged individual approach" has been replaced by a paradigm of teamwork. Here the emphasis in design has evolved toward a cooperative approach. This is conceptualized by Frank LeFasto and Carl Larson, who in their book *When Teams Work Best* hold that teams are "groups of people who design new products, stage dramatic productions, climb mountains, fight epidemics, raid crack houses, fight fires"[8] or pursue an unlimited list of present and future objectives. The paradigm recognizes that to be effective, we need not only groups of people who are technically competent but also those who are good at collaborating with one another to realize a common objective.[9] If we are to succeed by the new paradigm, we have to act synergistically.

According to Stokes, "the differing goals of basic and applied research make these types of research conceptually distinct."[10] Basic research is defined by the fact that it seeks to widen understanding of the phenomena of a scientific field—it is guided by the quest to further knowledge. While Bush felt that basic and applied research were in discord at least to some degree, Stokes points out that "the belief that the goals of understanding and use are inherently in conflict, and that the categories of basic and applied research are necessarily separate, is itself in tension with the actual experience of science."[11] To support this claim, many influential works of research are in fact driven by both of these goals. A prime example is the work of Louis Pasteur, who both sought to understand the microbiological processes he discovered and to apply this understanding to the prevention of the spoilage of vinegar, beer, wine, and milk,[12] Pasteur engaged in "whole mind" thinking as mentioned in Chapter 1.

Similarly, these goals of understanding and use are very closely related, as Stokes notes: The traditional fear of earthquakes, storms, droughts, and floods brought about the scientific fields of seismology, oceanic science, and atmospheric science. However, the idea that there is disparity between basic and applied research is captured in the "linear model" of the dynamic form of the postwar paradigm. It is important to keep in mind, though, that in the dynamic flow model, each successive stage depends on the stage before it (see Fig. 2.11). Note the similarity of this model with the stepwise design model discussed in Chapter 1.

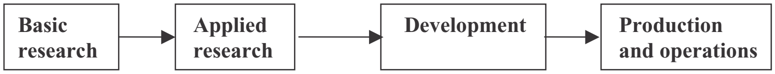


Figure 2.11 Progression from basic research to product or system realization.

This simple model of scientific advances in science being made applicable through a dynamic, yet stepwise flow from science to technology is widely accepted in research and development in many scientific disciplines. The process has come to be called *technology transfer*, as it describes the movement from basic science to technology. The first step in this process is basic research, which charts the course for practical application, eliminates dead ends, and enables the applied scientist and engineer to reach a goal quickly and economically. Then, applied research involves the elaboration and application of the known. Here, scientists convert the possible into the actual. The final stage in the technological sequence, development, is the stage where scientists systematically adapt research findings into useful materials, devices, systems, methods, processes, and so on.[13]

The characterization of evolution from basic to applied science, including design, has been criticized for being too simple an account of the flow from science to technology. The oversimplification may be due to the effort of the scientific community in the post–World War II era to communicate these concepts to the public. However, in particular, the *one-way* flow from scientific discovery to technological innovation does not seem to fit with twenty-first-century science. The supposition that science exists entirely *outside* technology is rather absurd in today's way of thinking. In fact, throughout history there is seen a reverse flow, a flow from technology to the advancement of science. Examples date as far back as Johannes Kepler, who helped lead to the invention of the calculus of variations through studying the structure of wine casks in order to optimize their design. Therefore, history illustrates that science has progressively become more *technology derived*.[14]

Critics consider that "the terms basic and applied are, in another sense, not opposites. Work directed toward applied goals can be highly fundamental in character in that it has an important impact on the conceptual structure or outlook of a field. Moreover, the fact that research of such a nature that it can be applied does not mean that it is not also basic."[15]

We argue, rather, that design based on sound science is actually a synthesis of the goals of understanding and use. Good design, then, is the marriage of theory and practice. Although he was not a designer per se, Pasteur exemplifies this combination of theory and utility. The one-dimensional model of Figure 2.2 consists of a line with "basic research" on one end and "applied research" on the other (as though the two were polar opposites). We could try to force-fit Pasteur's world view into this model by placing his design paradigms at the center of the flow in Figure 2.12. However, Pasteur's equal and strong commitments to *understanding* the theory (microbiological processes) and to practice (controlling the effects of these processes) would cover the entire line segment. Arguably, Pasteur must instead be represented by *two points:* one at the basic research end of the spectrum and another at the applied research end of the

Figure 2.12 Research categorized according to knowledge and utility drivers.

From D. E. Stokes, *Pasteur's Quadrant*, The Brookings Institution, Washington, DC, 1997.

		Consideration of use?	
		No	Yes
Quest for fundamental understanding?	Yes	Pure basic research (e.g., Bohr)	Use-inspired basic research (e.g., Pasteur)
	No		Pure applied research (e.g., Edison)

spectrum. This placement led Stokes to suggest a different model that reconciles the shortcomings of this one-dimensional model (see Fig. 2.12).

This model can also be applied to universities and research institutes. For example, within a university, we could have a situation something like Figure 2.13. The science departments are concerned with knowledge building, the engineering departments with applied knowledge to understand how to solve society's problems, and university designers are interested in finding innovative ways to use this knowledge. For example, the university architect may know what research has led to a particular design but may want to synthesize better design solutions in terms of energy use, aesthetics, materials, and place. The architect is behaving much like Thomas Edison, who was most interested in utility and less interested in knowledge for knowledge's sake. In addition, the architect must work closely with the managers of the operations programs of the university, who maintain the systems called for by the designer. This is not to say that innovations do not come from the lower left box in Figure 2.13, because they clearly do. It simply means

Figure 2.13 University research categorized according to knowledge and utility drivers.

		Consideration of use?	
		No	**Yes**
Quest for fundamental understanding?	**Yes**	Physics and Chemistry Departments – **Pure basic research**	Engineering Departments – **Use-inspired basic research**
	No	Facilities and Maintenance Departments – **Operations only**	University Architect – **Pure applied research**

that their measures of success at the university stress operation and maintenance. In fact, the quadrants must all have feedback loops to one another.

This view can also apply to symbiotic relationships among institutions. Duke University is located at one of the points of the Research Triangle in North Carolina. The other two points are the University of North Carolina–Chapel Hill and North Carolina State University. All three schools have engineering programs, but their emphasis differs somewhat. Duke is recognized as a world leader in basic research, but its engineering school tends to place a greater emphasis on application of these sciences. For example, there is much collaboration between Duke's School of Medicine and the biomedical engineering program in Duke's Pratt School of Engineering. The University of North Carolina also has a world-renown medical school, but its engineering program is housed in the School of Public Health. So this engineering research tends to advance health by addressing environmental problems. North Carolina State is the first place that the state of North Carolina looks for designers, so engineers graduating from NC State are ready to design as soon as they receive their diplomas. However, NC State also has an excellent engineering research program that applies the basic sciences to solve societal problems. All of this occurs within the scientific community of the Research Triangle, exemplified by Research Triangle Park (RTP), which includes centers supported by private and public entities that have a particular interest in mind. In this way, the RTP researchers are looking for new products and better processes. The RTP can be visualized as the "Edison" of the Triangle, although research in the other two quadrants is ongoing in the RTP labs. This can be visualized in an admittedly oversimplified way, as in Figure 2.14.

In the seemingly elegant model, the degree to which a given body of research seeks to expand understanding is represented on the vertical access, and the degree

Consideration of use?

Quest for fundamental understanding?	**Less**	**More**
More	Engineering Science at Duke University– **Pure basic research**	Public Health Engineering at University of North Carolina– **Use-inspired basic research**
Less	Research Triangle Park Institutes– **Need driven research**	Engineering at North Carolina State University– **Pure applied research**

Figure 2.14 Simple differentiation of the knowledge and utility drivers in the design-related research ongoing at institutions at Research Triangle Park, North Carolina.

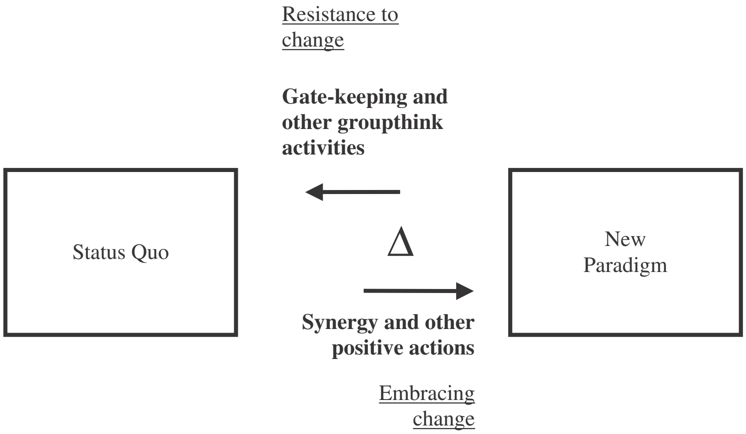


Figure 2.15 Resistance and openness to change: the difference between groupthink and synergy.

to which the research is driven by considerations of use is represented on the horizontal axis. A body of research that is equally committed to potential utility *and* to advancing fundamental understanding is represented as "use-inspired" research.[16]

For bold endeavors like green design and engineering, finding the right amount of shift is a challenge. For example, not changing is succumbing to groupthink, but changing the paradigm beyond what needs to be changed can be unprincipled, lacking in scientific rigor. Groupthink is a complicated concept. An undergraduate team in one of Vallero's recent courses thought of groupthink as a positive concept. Although they either did not read or disagreed with the assigned text's discussion of the matter, they made some good points about the value of group thinking in similar ways. It is amazing how creative students can be when they have not read the assigned material! One major value identified by the students is that when a group works together, it has synergies of ideas and economies of scale (see Fig. 2.15). Their point is well taken: Pluralistic views are often very valuable, but a group can also stifle differing opinions.

The key is finding the right balance between innovation and risk. Within this range is best, green practice.

NOTES AND REFERENCES

1. An ideal gas is one that conforms to Boyle's law and that has zero heat of free expansion (i.e., conforms to Charles' law).
2. Even solids can be fluids at a very large scale. For example, in plate tectonics and other expansive geological processes, solid rock will flow, albeit very slowly.

3. From C. Lee and S. Lin, Eds., *Handbook of Environmental Engineering Calculations*, McGraw-Hill, New York, 1999.
4. Newton actually coinvented the calculus with Gottfried Willhelm Leibniz in the seventeenth century. Both are credited with devising the symbolism and the system of rules for computing derivatives and integrals, but their notation and emphases differed. A debate rages as to who did what first, but both of these giants had good reason to revise the language of science (i.e., mathematics) to explain motion.
5. National Academy of Engineering, *The Engineer of 2020: Visions of Engineering in the New Century,* National Academies Press, Washington, DC, 2004.
6. I. Janus, *Groupthink: Psychological Studies of Policy Decisions and Fiascoes*, 2nd ed., Houghton Mifflin, Boston, MA, 1982.
7. V. Bush quoted by D. E. Stokes, *Pasteur's Quadrant*, The Brookings Institution, Washington, DC, 1997.
8. F. LaFasto and C. Larson, 2002, *When Teams Work Best*, Sage Publications, Inc., ThousandOaks, California.
9. J. Fernandez, Understanding group dynamics, *Business Line*, December 2, 2002.
10. Stokes, Pasteur's Quadrant, p. 6.
11. Ibid, p. 12.
12. Ibid.
13. Ibid., pp. 10–11.
14. Ibid., pp. 18–21.
15. H. Brooks, 1979, "Basic and Applied Research," *Categories of Scientific Research*, National Academy Press, Washington, DC, pp. 14–18.
16. Stokes, Pasteur's Quadrant, pp. 70–73.

chapter 3

Transitions

Before we can truly appreciate the significant progress in sustainable design, let us point to the evolution, even revolution, in our transition from neglect to regulation to prevention to sustaintainability. During the last quarter of the twentieth century, protecting the environment was focused almost exclusively on controlling pollutants. This was primarily under a sense of urgency that called for a reaction mode: cleaning up the most pressing and ominous problems. Toward the end of the century and into the twenty-first century, green approaches have emerged, but the emphasis has still been primarily on treating pollutants at the end of the process. Controls are placed on stacks, pipes, and vents. Emergency response and remediation are dedicated to spills, leaks, and waste sites. The process is changing slowly. Although this book focuses on new ways of thinking and embraces the ethos of green design, engineers and other designers need to be knowledgeable of current expectations. Quite likely, even the most forward-thinking engineering and design firms will need to address existing pollution. So we must consider the basics of pollution control, then prevention and sustainability, with an eye toward regenerative systems.

A BRIEF HISTORY

With recent strides made in taking a more integrated, proactive view of environmental design and protection, we hasten to point out the remarkable progress in environmental awareness, decision making, and actions in just a few short decades. In the last quarter of the twentieth century, advances and new environmental applications of science, engineering, and their associated technologies began to coalesce into an entirely new way to see the world, at least new to most of Western civilization. Ancient cultures on all continents, including the Judeo-Christian belief systems, had warned that humans could destroy the resources bestowed upon us unless the view as stewards and caretakers of the environment was taken seriously. Scientifically based progress was one of the major factors behind the exponential growth of threats to the environment. Environmental controls grew out of the same science, which is now part of an ethos that builds environmental values into the design process.

Science is the explanation of the physical world; engineering encompasses applications of science to achieve results. Thus, what we have learned about the environment by trial and error has grown incrementally into what is now standard practice of environmental science and engineering. This heuristically attained knowledge has come at a great cost in terms of the loss of lives and diseases associated with mistakes, poor decisions (at least in retrospect), and the lack of appreciation of environmental effects, but progress is being made all the same. Environmental awareness is certainly more "mainstream" and less a polarizing issue than it was in the 1970s and 1980s. There has been a steady march of advances in environmental science and engineering for several decades, as evidenced by the increasing number of Ph.D. dissertations and credible scientific journal articles addressing myriad environmental issues.

The environmental movement is relatively young. The emblematic works of Rachel Carson, Barry Commoner, and others in the 1960s were seen by many as passing fads. In the 1970s and 1980s, the movement was truly tested. We saw "we versus them" dramas play out throughout society: jobs versus the environment, safety versus the environment, contemporary life versus the environment, and even religion versus the environment. However, these disputes seemed to dissipate when the facts were fully scrutinized. Surely, a number of businesses *did indeed fail* and *jobs were lost,* but quite often the pollution was merely one of a number of their inefficiencies.

Decision makers in the private and public sectors have since come to recognize environmental quality not as an option, but as a design constraint. It is even recognized by most politicians, no matter their party affiliation, that clean air, water, land, and food are almost universally accepted expectations of the populace. This did not eliminate major debates on *how* to achieve a livable environment, but set the stage for green design.

How Clean Is Clean?

Even within the environmental professional and scientific communities, we continue to debate "how clean is clean" *ad nauseum*. For example, we can present the same data regarding a contaminated site to two distinguished environmental engineers. One will recommend active cleanup, such as a pump-and-treat approach, and the other will recommend a passive approach, such as natural attenuation, wherein the microbes and abiotic environment are allowed to break down the contaminants over an acceptable amount of time. Both will probably strongly recommend ongoing monitoring to ensure that the contaminants are in fact breaking down and to determine that they are not migrating away from the site. Does this mean that one is less competent or environmentally aware than the other? Certainly not.

Various design recommendations result from judgments about the system at hand, notably the initial and boundary conditions, control volume, and the constraints and drivers that we discussed in Chapter 2. In each expert's judgment, the solution designed calls for different approaches. For example, a site on Duke University's property was used to bury low-level radioactive waste and spent chemicals. The migration of one of these chemicals, the highly toxic paradioxane, was modeled. A comparison of the effectiveness of active versus passive design is shown in Figure 3.1. Is this difference sufficiently significant to justify active removal and remediation instead of allowing nature to take its course?

Both approaches have risks. Active cleanup potentially exposes workers and the public during removal. There may even be avenues of contamination made possible by the action that would not exist if no action were taken. Conversely, in many cases, without removal of the contaminant, it could migrate to aquifers and surface water that are the sources of drinking water, or could remain a hazard for decades if the contaminant is persistent and not amenable to microbial degradation. Thus, green engineering requires consideration of risk management, and managing these risks requires thoughtful consideration of all options.

Risk management is an example of optimization. However, optimizing among variables is not usually straightforward for green engineering applications. Optimization models often apply algorithms to arrive at a net benefit/cost ratio, with the option selected being the one with the largest value (i.e., greatest quantity of benefits compared to costs). To economists and ethicists this is a utilitarian approach. There are numerous challenges when using such models in environmental decision making. Steven Kelman of Harvard University was one of the first to articulate the weaknesses and dangers of taking a purely utilitarian approach in managing environmental, safety, and health risks.[1] Kelman asserts that in such risk management decisions, a larger benefit/cost ratio does not always point to the correct decision. He also opposes the use of dollars (i.e., monetization of nonmarketed benefits or costs) to place a value on environmental resources, health, and quality of life. He uses a logical technique of *reductio ad absurdum* (from the Greek, η‘ εις το αδυνατον απαγωγη, "reduction to the impossible"), where an assumption is made for the sake of argument, a result found, but it is so absurd that the original assumption must have been wrong.[2] For example, the consequences of an act, whether positive or negative, can extend far beyond the act itself. Kelman gives the example of telling a lie. Using the pure benefit/cost ratio, if the person telling the lie has much greater satisfaction (however that is quantified) than the dissatisfaction of the lie's victim, the benefits would outweigh

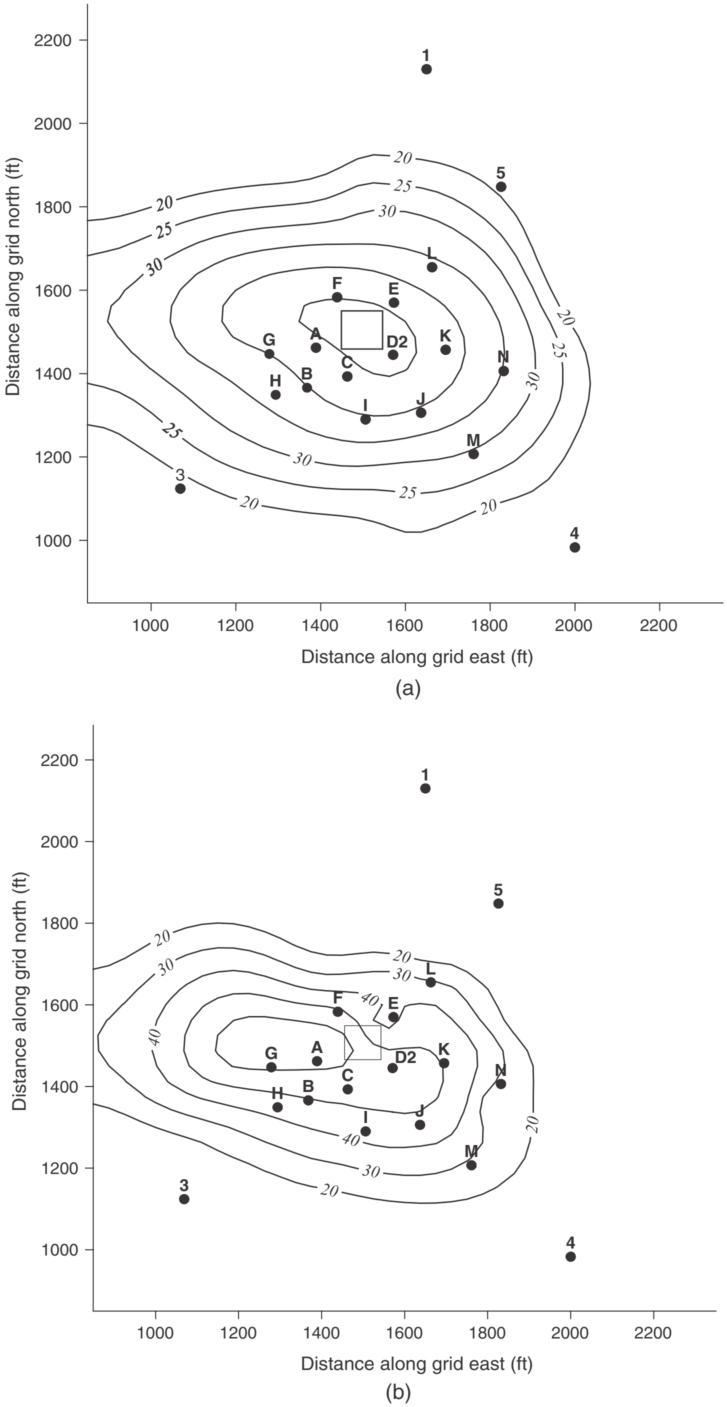


Figure 3.1 Duke Forest gate 11 waste site in North Carolina: (a) modeled paradioxane plume after 50 years of natural attenuation; (b) paradioxane plume modeled after 10 years of pump and recharge remediation. Numbered points are monitoring wells. The difference in plume size from intervention versus natural attenuation is an example of the complexity of risk management decisions; that is, does the smaller predicted plume justify added costs, possible risk trade-offs from pumping (e.g., air pollution), and disturbances to soil and vegetation?

From M. A. Medina, Jr., W. Thomann, J. P. Holland, and Y.-C. Lin, "Integrating parameter estimation, optimization and subsurface solute transport," *Hydrological Science and Technology*, 17, 259–282, 2001. Used with permission of the first author.

the cost and the decision would be morally acceptable. At a minimum, the effect of the lie on future lie-telling would have to be factored into the ratio, as would other cultural norms.

Another of Kelman's examples of flaws of utilitarianism is the story of two friends on an Arctic expedition, wherein one becomes fatally ill. Before dying, he asks that the friend return to that very spot in the Arctic ice in 10 years to light a candle in remembrance. The friend promises to do so. If no one else knows of the promise and the trip would be a great inconvenience, the benefit/cost approach instructs him not to go (i.e., the costs of inconvenience outweigh the benefit of the promise because no one else knows of the promise). These examples point to the fact that benefit/cost information is valuable, but care must be taken in choosing the factors that go into the ratio, properly weighing subjective and nonquantifiable data, ensuring that the views of those affected by the decision are considered properly and being mindful of possible conflicts of interest and the undue influence of special interests. This is further complicated in sustainable design, since the benefits may not be derived for decades and possibly by people other than those enduring the costs and risks.

The challenge of green engineering and design is to find ways to manage environmental risks and impacts in a way that is underpinned by sound science and to approach each project from a "site-wide" perspective that combines health and ecological risks with land-use considerations. This means that whatever residual risk is allowed to remain is based on both traditional risk outcomes (disease, endangered species) *and* future land uses (see Fig. 3.2). This is the temporal perspective at the heart of sustainable design. Even a very attractive near-term project may not be as good when viewed from a longer-term perspective. Conversely, a project with seemingly large initial costs may in the long run be the best approach. This opens the door for selecting projects with larger initial risks. Examples of site-based risk management include asbestos and lead remedies, where workers are subjected to the threat of elevated concentrations of toxicants but the overall benefits of the action are deemed necessary to protect children now and in the future. In an integrated engineering and design project, a risk that is widely distributed in space and time (i.e., numerous buildings with the looming threat to children's health for decades to come) is avoided in favor of a more concentrated risk that can be controlled (e.g., safety protocols, skilled workers, protective equipment, removal and remediation procedures, manifests and controls for contaminated materials, and ongoing monitoring of fugitive toxicant releases). It even allows a view toward what to do after the useful life of a building or product (i.e., design for disassembly: DfD).

This combined risk and land-use approach also helps to moderate the challenge of "one size fits all" in environmental cleanup. That is, limited resources may be devoted to other community objectives if the site does not have to be cleaned to the level prescribed by a residential standard. This does not mean that

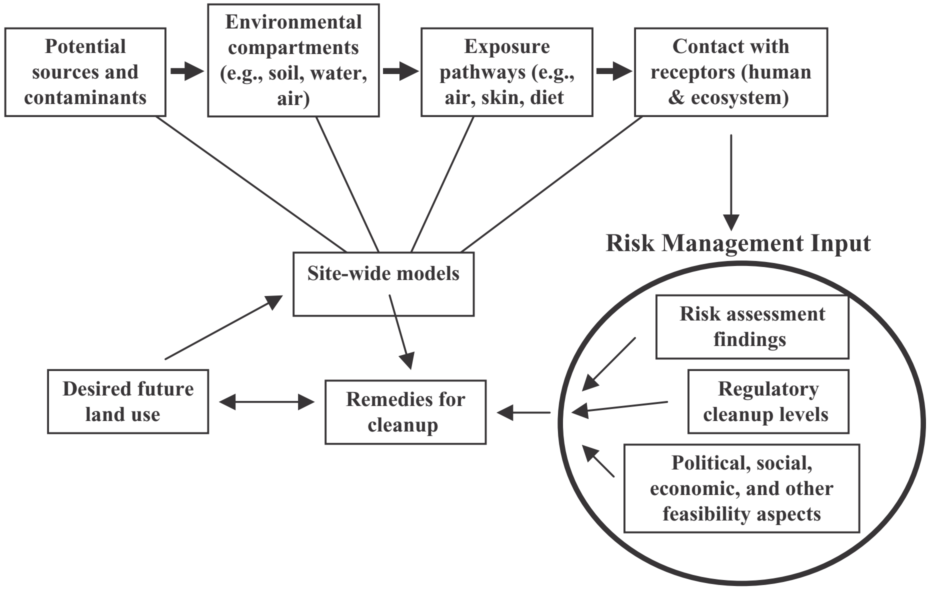


Figure 3.2 Site-wide cleanup model based on targeted risk and future land use.

Adapted from J. Burger, C. Powers, M. Greenberg, and M. Gochfeld, "The role of risk and future land use in cleanup decisions at the department of energy," *Risk Analysis,* 24(6), 1539–1549., 2004

the site can be left to be "hazardous," only that the cleanup level can be based on a land use other than residential, where people are to be protected in their daily lives. For example, if the target land use is similar to the sanitary landfill common to most communities in the United States, the protection of the general public is achieved through measures beyond concentrations of a contaminant. These measures include allowing only authorized and adequately protected personnel in the landfill area, barriers, and leachate collection systems to ensure that contamination is confined within certain areas within the landfill and security devices and protocols (fences, guards, and sentry systems) to limit the opportunities for exposures and risks by keeping people away from more hazardous areas. This can also be accomplished in the private sector. For example, turnkey arrangements can be made so that after the cleanup (private or governmental) meets the risk/land-use targets, a company can use the remediated site for commercial or industrial uses. Again, the agreement must include provisions to ensure that the company has adequate measures in place to keep risks to workers and others below prescribed targets, including periodic inspections, permitting, and other types of oversights by governmental entities to ensure compliance with agreements to keep the site clean (i.e., *closure* and *post closure agreements*).

The American Society of Civil Engineers was the first of the engineering discipline societies to codify this into the norms of practice. The first canon of the ASCE code of ethics now reads: "Engineers shall hold paramount the safety, health and welfare of the public and shall strive to comply with the principles of sustainable development in the performance of their professional duties."[3] The code's most recent amendment on November 10, 1996, incorporated the principle of sustainable development. As a subdiscipline of civil engineering, much of the environmental engineering mandate is encompassed under engineering professional codes in general and more specifically in the ASCE. The code mandates four principles that engineers abide by to uphold and to advance the "integrity, honor, and dignity of the engineering profession:"

1. Using their knowledge and skill for the enhancement of human welfare and the environment
2. Being honest and impartial and serving with fidelity the public, their employers, and clients
3. Striving to increase the competence and prestige of the engineering profession
4. Supporting the professional and technical societies of their disciplines

The code further articulates seven fundamental canons:

1. Engineers shall hold paramount the safety, health, and welfare of the public and shall strive to comply with the principles of sustainable development in the performance of their professional duties.
2. Engineers shall perform services only in areas of their competence.
3. Engineers shall issue public statements only in an objective and truthful manner.
4. Engineers shall act in professional matters for each employer or client as faithful agents or trustees, and shall avoid conflicts of interest.
5. Engineers shall build their professional reputation on the merit of their services and shall not compete unfairly with others.
6. Engineers shall act in such a manner as to uphold and enhance the honor, integrity, and dignity of the engineering profession.
7. Engineers shall continue their professional development throughout their careers, and shall provide opportunities for the professional development of those engineers under their supervision.

The first canon is a direct mandate for the incorporation of green design principles. The remaining canons prescribe and proscribe activities to ensure trust. It is important to note that the code applies to all civil engineers, not just environmental engineers. Thus, even a structural engineer must "hold paramount" the public health and environmental aspects of any project and must seek ways to ensure that the structure is part of an environmentally sustainable approach. This is an important aspect of sustainability, in that it is certainly not deferred to the "environmental" professions but is truly an overarching mandate for all professions (including medical, legal, and business-related professionals). That is why environmental decisions must incorporate a wide array of perspectives, while being based on sound science. The first step in this inclusive decision-making process, then, is to ensure that every stakeholder understands the data and information gathered when assessing environmental conditions.

With the emergence of a newer, greener era, companies and agencies have been looking beyond ways to treat pollution to find better processes to prevent environmental harm in the first place. In fact, the adjective *green* has been increasingly showing up in front of many disciplines (e.g., green chemistry, green engineering, green architecture), as has the adjective *sustainable*. Increasingly, companies have come to recognize that improved efficiencies save time, money, and other resources in the long run. Hence, companies are thinking systematically about the entire product stream in numerous ways:

- Applying sustainable development concepts, including the framework and foundations of green design and engineering models
- Applying the design process within the context of a sustainable framework, including considerations of commercial and institutional influences
- Considering practical problems and solutions from a comprehensive standpoint to achieve sustainable products and processes
- Characterizing waste streams resulting from designs and increasingly adopting a "design for disassembly" ethos.
- Understanding how first principles of science, including thermodynamics and mechanics, must be integral to sustainable designs in terms of mass and energy relationships, including reactors, heat exchangers, and separation processes
- Applying creativity, system integration, and originality in group product and building design projects

Major incidents and milestones remind us of how delicate and vulnerable environmental resources can be. They also remind us that, in all engineering and design, the system is only as robust as its weakest component. Many of these incidents occurred as a confluence of numerous factors and events. The retrospective view also gives us information on what may yet occur in the future. Like many other trends of the late twentieth and early twenty-first centuries, many people have a "top 10 list" of the most crucial events that have shaped the environmental agenda. Some of the most notorious and infamous incidents include:

- *Torrey Canyon* tanker oil spill in the English Channel (March 18, 1967)
- Love Canal hazardous waste site, Niagara Falls, New York (discovered in the 1970s)
- Seveso, Italy, explosion disaster, release of dioxin (July 10, 1976)
- Bhopal, India, methylisocyanate explosion and toxic cloud (December 3, 1984)
- *Exxon Valdez* tanker oil spill, Prince William Sound, Alaska (March 24, 1989)
- *Prestige* tanker oil spill, off the Spanish coast (November 13, 2002)

These all involved chemical pollutants, but important nuclear events have also been extremely influential in our perception of pollution and threats to public health. Most notably, the cases of Three Mile Island, in Dauphin County, Pennsylvania (March 28, 1979) and the Chernobyl nuclear power-plant disaster in the Ukraine (April 26, 1986) have had an unquestionable impact not only on nuclear power but also on aspects of environmental policy, such as community "right-to-know" and the importance of risk assessment, management, and communication.

Numerous defense- and war-related incidents have also had a major influence on the public's perception of environmental safety. For example, the atomic bombings of Hiroshima and Nagasaki (August 6 and August 9, 1945, respectively) were the world's first entrées to the chronic illness and mortality (e.g., leukemia, radiation disease) that could be linked directly to radiation exposure. Similarly, use of the defoliant Agent Orange during the Vietnam War (used between 1961 and 1970) made us aware of the importance of the *latency period*, so that we now know that possible effects may not be manifested until years or decades after pesticide exposure. The Agent Orange problem also illustrates the problem of uncertainty in characterizing and enumerating effects. There is no consensus on whether the symptoms and disorders suggested as being linked to Agent Orange are sufficiently strong and well documented (i.e., provide weight of evidence) to support cause and effect. However, there is enough anecdotal evidence that the effects from these exposures should at least be considered to be plausible.

Let us consider three cases that demonstrate the problem of nonintegrative approaches to design.

Donora, Pennsylvania[4]

After World War II, the United States was concerned with getting the economy and the American way of life back on track. We wanted to produce more of what Americans wanted, including cars, airplanes, roads, toys, food, and all the trappings of the American Dream. The industrial machine was more than happy to oblige. Unfortunately, it was during this growth spurt that we tasted the ill-effects of single-minded industrial development.

In 1948, the United States experienced its first major air pollution catastrophe, in Donora, Pennsylvania. Contaminant releases from a number of industries, including a sulfuric acid plant, a steel mill, and a zinc production plant, became trapped in a valley by a temperature inversion and produced an unbreathable mixture of fog and pollution (see Fig. 3.3). Six thousand people suffered illnesses ranging from sore throats to nausea. There were 20 deaths in three days. Sulfur dioxide (SO_2) was estimated to reach levels as high as 5500 $\mu g\ m^{-3}$. Compare this to the current U.S. health standard of 365 μg^{-3} in the ambient air (24-hr. average).

This particular form of sulfur is highly toxic, but many other compounds of sulfur are essential components of biological systems. In the wrong place at the wrong time, these compounds are hazardous to health, welfare, and the environment (see the discussion box "Sulfur and Nitrogen Compound: The Form Makes the Harm").

A common feature of many air pollution episodes is thermal inversion. In the air, meteorology helps to determine opportunities to control the atmospheric transport of contaminants. For example, industries are often located near each other, concentrating the release of pollutants. Cities and industrial centers have often been located near water bodies. This means that they are inordinately located in river valleys and other depressions. This increases the likelihood of occurrences of ground-based inversions, elevated inversions, valley winds, shore breezes, and city heat islands (see Fig. 3.3). When this happens, as it did in Donora, the pollutants become locked into air masses with little or no chance of moving out of the respective areas. Thus, concentrations of the pollutants can quickly pose substantial risks to public health and the environment.

For a town of only 14,000 people, the number of deaths in such a short time was unprecedented; in fact, the town did not have enough coffins to accommodate the burials. The Donora incident is important because it was the first dramatic evidence that unchecked pollution was an American problem. It was among the first real warnings against unbridled, nonintegrative decision making. Pollution had morphed from merely a nuisance and an aesthetic problem to an urgent public health concern in North America and the world.

The green engineering lesson is the need for wise site selection of facilities that generate, process, and store contaminants as the first step in preventing

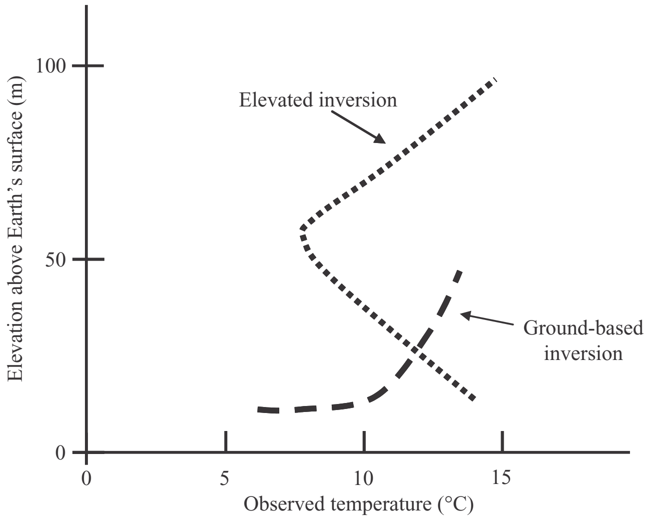


Figure 3.3 Two types of thermal inversions that contribute to air pollution.

or reducing the likelihood that they will move. On a smaller scale, the same logic can be applied to siting a single building. Micrometeorology can have a profound influence on air flow. Also, the collective effects from a number of buildings can affect the quality of the neighborhood. Each increasing building may exponentially approach a given development's carrying capacity.

Sulfur and Nitrogen Compounds: Harm Follows Form

Any farmer worth his or her salt knows that the elements sulfur (S) and nitrogen (N) are the key elements of fertilizers. Along with phosphorus and potassium, S and N compounds provide macro- and micronutrients to ensure productive crop yields. Conversely, ask an environmental expert and you are likely to hear about numerous S and N compounds that can harm the health of humans, that can adversely affect the environment, and that can lead to welfare impacts, such as the corrosion of buildings and other structures and diminished visibility due to the formation of haze. So S and N must be understood from a life-cycle perspective. Such nutrients also demonstrate the concept that pollution is often a resource that is simply in the wrong place.

The reason that sulfur and nitrogen pollutants are often lumped together may be that their oxidized species [e.g., sulfur dioxide (SO_2) and nitrogen dioxide (NO_2)] form acids when they react with water. The lowered pH is responsible for many environmental problems. Another reason may be that many sulfur and nitrogen pollutants result from combustion. Whatever the reasons, however, sulfur and nitrogen pollutants actually are very different in their sources and in the processes that lead to their emissions.

Sulfur is present in most fossil fuels, usually higher in coal than in crude oil. Prehistoric plant life is the source of most fossil fuels. Most plants contain sulfur as a nutrient, and as the plants become fossilized, a fraction of the sulfur volatilizes (i.e., becomes a vapor) and is released. However, some sulfur remains in the fossil fuel and can be concentrated because much of the carbonaceous matter is driven off. Thus, the sulfur in the coal is available to react with oxygen when the fossil fuel is combusted. In fact, the sulfur content of coal is an important characteristic in its economic worth; the higher the sulfur content, the less it is worth. So the lower the content of sulfur and volatile constituents and the higher the carbon content, the more valuable the coal. Since combustion is the combination of a substance (fuel) with molecular oxygen (O_2) in the presence of heat [denoted by the Δ above the arrow in the one-way (i.e., irreversible) reaction], the reaction for complete or efficient combustion of a hydrocarbon results in the formation of carbon dioxide and water:

$$(CH)_x + O_2 \xrightarrow{\Delta} CO_2 + H_2O \tag{B3.1}$$

Fossil fuels contain other elements which also oxidize. When sulfur is present, the side reaction forms oxides of sulfur. Thus, sulfur dioxide is formed as

$$S + O_2 \xrightarrow{\Delta} SO_2 \tag{B3.2}$$

Actually, many other oxidized forms of sulfur can form during combustion, so air pollution experts refer to them collectively as SO_x, a term seen commonly in air pollution literature.

Similarly, nitrogen compounds also form during combustion, but their sources are very different from those of sulfur compounds. Recall that the *troposphere*, the part of the atmosphere where we live and breathe, is made up mainly of molecular nitrogen (N_2). More than three-fourths of the troposphere is N_2, so the atmosphere itself is the source of much of the nitrogen that forms oxides of nitrogen (NO_x). Because N_2 is relatively nonreactive under most atmospheric conditions, it seldom enters into chemical reactions, but under high pressure and at very high temperatures, it will react with O_2:

$$N_2 + O_2 \xrightarrow{\Delta} 2NO \tag{B3.3}$$

Where will we find conditions such that N_2 will react this way? Actually, it is sitting in your driveway or garage. The automobile's internal combustion engine is a major source of oxides of nitrogen, as are electricity generating stations, which use boilers to make steam to turn turbines to convert mechanical energy into electrical energy. Approximately 90 to 95% of the nitrogen oxides generated in combustion processes are in the form of nitric oxide (NO), but like the oxides of sulfur, other nitrogen oxides can form, especially nitrogen dioxide (NO_2), so air pollution experts refer to NO and NO_2 collectively as NO_x. In fact, in the atmosphere the NO emitted is quickly converted photochemically to nitrogen dioxide (NO_2). Such high-temperature/high-pressure conditions exist in internal combustion engines, like those in automobiles and other "mobile sources." Thus, NO_x is one of the major mobile source air pollutants (others include particulate matter, hydrocarbons, carbon monoxide, and in some countries, the heavy metal lead).

In addition to atmospheric nitrogen, other sources exist, particularly the nitrogen in fossil fuels. The nitrogen oxides generated from atmospheric nitrogen are known as *thermal* NO_x since they form at high temperatures, such as near burner flames in combustion chambers. Nitrogen oxides that form from the fuel or feedstock are called *fuel* NO_x. Unlike the sulfur compounds, a significant fraction of the fuel nitrogen remains in the bottom ash or in unburned aerosols in the gases leaving the combustion chamber (i.e., the fly ash). Nitrogen oxides can also be released from nitric acid plants and other types of industrial processes involving the generation and/or use of nitric acid (HNO_3).

Nitric oxide is a colorless, odorless gas and is essentially insoluble in water. Nitrogen dioxide has a pungent acid odor and is somewhat soluble in water. At low temperatures such as those often present in the ambient atmosphere, NO_2 can form the molecule $NO_2–O_2N$ or simply N_2O_4, which consists of two identical simpler NO_2 molecules. This is known as a *dimer*. The dimer N_2O_4 is distinctly reddish brown and contributes to the brown haze that is often associated with photochemical smog incidents.

Both NO and NO_2 are harmful and toxic to humans, although atmospheric concentrations of nitrogen oxides are usually well below the concentrations expected to lead to adverse health effects. The low concentrations are a result of the moderately rapid reactions that occur when NO and NO_2 are emitted into the atmosphere. Much of the concern for regulating NO_x emissions is to suppress the reactions in the atmosphere that generate the highly reactive molecule ozone (O_3). Nitrogen oxides play key roles as important reactants in O_3 formation. Ozone forms photochemically (i.e., the reaction is caused or accelerated by light energy) in the lowest level of the atmosphere, the troposphere. Nitrogen dioxide is the principal gas responsible for absorbing sunlight needed for these photochemical reactions. So in the presence of sunlight, the NO_2 that forms from the NO stimulates the photochemical smog-forming reactions incrementally because nitrogen dioxide is very efficient at absorbing sunlight in the ultraviolet portion of its spectrum. This is why ozone episodes are more common in the summer and in areas with ample sunlight. Other chemical ingredients (i.e., ozone precursors) in O_3 formation include volatile organic compounds and carbon monoxide. Governments around the world regulate the emissions of precursor compounds to diminish the rate at which O_3 forms. Many compounds contain both nitrogen and sulfur along with the typical organic elements (carbon, hydrogen, and oxygen). The reaction for the combustion of such compounds, in general form, is

$$C_aH_bO_cN_dS_e + 4a + b - 2c \rightarrow aCO_2 + \frac{b}{2}H_2O + \frac{d}{2}N_2 + eS \qquad \text{(B3.4)}$$

This reaction demonstrates the incremental complexity as additional elements enter the reaction. In the real world, pure reactions are rare. The environment is filled with mixtures. Reactions can occur in sequence, in parallel, or both. For example, a feedstock to a municipal incinerator contains myriad types of wastes, from garbage to household chemicals to commercial wastes, and even small (and sometimes large) amounts of industrial wastes that may be dumped illegally. For example, the nitrogen content of typical cow manure is about 5 kg per metric ton (about 0.5%). If the fuel used to burn the waste also contains sulfur along with the organic matter, the five elements will react according to the stoichiometry of reaction (B3.4). Thus, from a green engineering perspective, burning municipal waste to generate electricity may also release harmful compounds.

Certainly, combustion specifically and oxidation generally are very important processes that lead to nitrogen and sulfur pollutants. But they are certainly not the only ones. In fact, we need to explain what oxidation really means. In the environment, oxidation *and* reduction occur. An *oxidation–reduction* (or *redox*) *reaction* is the simultaneous loss of an electron (oxidation) by one substance joined by an electron gain (reduction) by another in the same reaction. In oxidation, an element or compound loses (i.e., donates) electrons. Oxidation also occurs when oxygen atoms are gained or when hydrogen atoms are lost. Conversely, in reduction, an element or compound gains (i.e., captures) electrons. Reduction also occurs when oxygen atoms are lost or when hydrogen atoms are gained. The nature of redox reactions means that each oxidation–reduction reaction is a pair of two simultaneously occurring *half-reactions*. The formation of sulfur dioxide and nitric oxide by acidifying molecular sulfur is a redox reaction:

$$S(s) + NO_3^-(aq) \rightarrow SO_2(g) + NO(g) \qquad \text{(B3.5)}$$

The designations in parentheses give the physical phase of each reactant and product: “s” for solid, “aq” for aqueous, and “g” for gas. The oxidation half-reactions for this reaction are

$$S \rightarrow SO_2 \tag{B3.6}$$

$$S + 2H_2O \rightarrow SO_2 + 4H^+ + 4e^- \tag{B3.7}$$

The reduction half-reactions for this reaction are

$$NO_3^- \rightarrow NO \tag{B3.8}$$

$$NO_3^- + 4H^+ + 3e^- \rightarrow NO + 2H_2O \tag{B3.9}$$

Therefore, the balanced oxidation-reduction reactions are

$$4NO_3^- + 3S + 16H^+ + 6H_2O \rightarrow 3SO_2 + 16H^+ + 4NO + 8H_2O \tag{B3.10}$$

$$4NO_3^- + 3S + 4H^+ \rightarrow 3SO_2 + 4NO + 2H_2 \tag{B3.11}$$

Oxidation–reduction reactions are not only responsible for pollution but are also very beneficial. Redox reactions are part of essential metabolic and respiratory processes. Redox is commonly used to treat wastes (e.g., to ameliorate toxic substances and to detoxify wastes) by taking advantage of electron-donating and electron-accepting microbes or by abiotic chemical redox reactions. For example, in drinking water treatment, a chemical oxidizing or reducing agent is added to the water under controlled pH. This reaction raises the valence of one reactant and lowers the valence of the other. Thus, redox removes compounds that are “oxidizable,” such as ammonia, cyanides, and certain metals, including selenium, manganese, and iron. It also removes other “reducible” metals, such as mercury (Hg), chromium (Cr), lead (Pb), silver (Ag), cadmium (Cd), zinc (Zn), copper (Cu), and nickel (Ni). Oxidizing cyanide (CN^-) and reducing Cr^{6+} to Cr^{3+} are examples in which the toxicity of inorganic contaminants can be greatly reduced by redox.*

*Redox reactions are controlled in closed reactors with rapid-mix agitators. Oxidation–reduction probes are used to monitor reaction rates and product formation. The reactions are exothermic and can be very violent when the heat of reaction is released, so care must be taken to use only dilute concentrations, along with careful monitoring of batch processes.

A reduced form of sulfur that is highly toxic and an important pollutant is hydrogen sulfide (H_2S). Certain microbes, especially bacteria, reduce nitrogen and sulfur, using them as energy sources through the acceptance of electrons. For example, sulfur-reducing bacteria can produce hydrogen sulfide (H_2S) by chemically changing oxidized forms of sulfur, especially sulfates (SO_4). To do so, the bacteria must have access to the sulfur; that is, it must be in the water, which can be surface water, groundwater, or the water in soil and sediment. These sulfur reducers are often *anaerobes*, bacteria that live in water where concentrations of molecular oxygen (O_2) are deficient. The bacteria remove the O_2 molecule from the sulfate, leaving only the sulfur, which in turn combines with hydrogen (H) to form gaseous H_2S. In groundwater, sediment, and soil water, H_2S is formed from the anaerobic or nearly anaerobic decomposition of deposits of organic matter (e.g. plant residues). Thus, redox principles can be used to treat H_2S contamination; that is, the compound can be oxidized using a number of different oxidants (see Table B3.1). Strong oxidizers such as molecular oxygen and hydrogen peroxide oxidize the reduced forms of sulfur, nitrogen, or any reduced compound most effectively.

Table B3.1 Theoretical Amounts of Various Agents Required to Oxidize 1 mg L^{-1} of Sulfide Ion

Oxidizing Agent	Amount (mg L^{-1}) Needed to Oxidize 1 mg L^{-1} of S_2^- (based on practical observations)	Theoretical Stoichiometry (mg L^{-1})
Chlorine (Cl_2)	2.0–3.0	2.2
Chlorine dioxide (ClO_2)	7.2–10.8	4.2
Hydrogen peroxide (H_2O_2)	1.0–1.5	1.1
Potassium permanganate ($KMnO_4$)	4.0–6.0	3.3
Oxygen (O_2)	2.8–3.6	0.5
Ozone (O_3)	2.2–3.6	1.5

Source: Water Quality Association, Ozone Task Force Report, "Ozone for POU, POE and small water system applications," WQA, Lisle, IL, 1999.

Ionization is also important in environmental reactions. This is due to the configuration of electrons in an atom. The arrangement of the electrons in the atom's outermost shell (i.e., valence) determines the ultimate chemical behavior of the atom. The outer electrons become involved in transfer to and sharing with shells in other atoms (i.e., forming new compounds and ions). An atom will gain or lose valence electrons to form a stable ion that has the same number of electrons as the noble gas nearest the atom's atomic number. For example, the nitrogen cycle (see Figure B3.1) includes three principal forms that are soluble in water under environmental conditions: the cation (positively charged ion) ammonium (NH_4^+) and the anions (negatively charged ions) nitrate (NO_3^-) and nitrite (NO_2^-). Nitrates and nitrites combine with various organic and inorganic compounds. Once taken into the body, NO_3^- is converted to NO_2^-. Since NO_3^- is soluble and readily available as a nitrogen source for plants (e.g., to form plant tissue compounds such as amino acids and proteins), farmers are the biggest users of NO_3^- compounds—in commercial fertilizers (although even manure can contains high levels of NO_3^-).

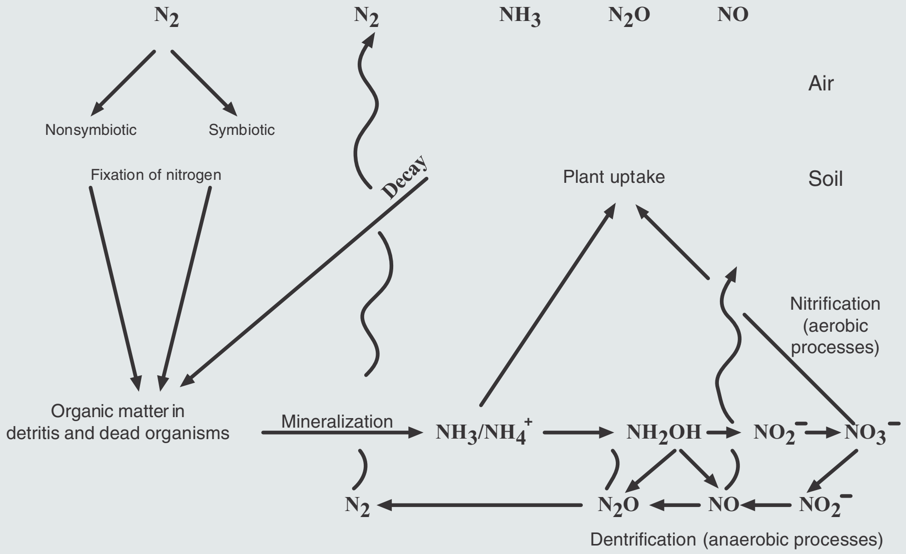


Figure B3.1 Biochemical nitrogen cycle.

Ingesting high concentrations of nitrates (e.g., in drinking water) can cause serious short-term illness and even death. A serious illness in infants, known as methemoglobinemia, is due to the body's conversion of nitrate to nitrite, which can interfere with the oxygen-carrying capacity of the blood. Especially in small children, when nitrates compete successfully against molecular oxygen, the blood carries methemoglobin (as opposed to healthy hemoglobin), giving rise to clinical symptoms. At 15 to 20% methemoglobin, children can experience shortness of breath and blueness of the skin (i.e., clinical cyanosis). At 20 to 40% methemoglobin, hypoxia will result. This acute condition can cause a child's health to deteriorate rapidly over a period of days, especially if the water source continues to be used. Long-term elevated exposure to nitrates and nitrites can cause an increase in the kidneys' production of urine (diuresis), increased starchy deposits, and hemorrhaging of the spleen.* This whole problem can be avoided if we vigilently hold to a sustainable viewpoint. That is, using too little or too much nitrogen fertilizer is problematic, the former resulting in reduced crop yields and the latter in nitrates in drinking water. Thus, the life cycle of the fertilizer application and the mass balance of nitrogen must be seen as drivers and constraints of this disease.

Nutrients demonstrate the importance of cycles. Compounds of nitrogen and sulfur are important in every environmental medium. They exist as air pollutants, water pollutants, indicators of eutrophication (i.e., nutrient enrichment), ecological conditions, and acid rain. They are some of the best examples of the need for a systematic viewpoint. Nutrients are valuable, but in the wrong place under the wrong conditions, they become pollutants.

*U.S. Environmental Protection Agency, Technical Fact Sheet, "National primary drinking water regulations" http://www.epa.gov/OGWDW/hfacts.html, U.S. EPA, Washington, DC, 1999.

Love Canal, New York

The seminal and arguably the most infamous toxic waste case is the contamination in and around Love Canal, New York. The beneficent beginnings of the case belie its infamy. In the nineteenth century, William T. Love saw an opportunity for electricity generation from Niagara Falls and the potential for industrial development. Thus, Love Canal began with a "green" principle (multiple use). To achieve this, Love planned to build a canal that would also allow ships to pass around the Niagara Falls and travel between the two great lakes, Erie and Ontario. The project started in the 1890s, but soon floundered, due to inadequate financing and to the development of alternating current, which made it unnecessary for industries to locate near a source of power production. The Hooker Chemical Company purchased the land adjacent to the canal in the early 1900s and constructed a production facility. In 1942, Hooker Chemical began disposal of its industrial waste in the canal. This was wartime in the United States, and there was little concern for possible environmental consequences. Hooker Chemical (which later became Occidental Chemical Corporation) disposed of over 21,000 tons of chemical wastes, including halogenated pesticides, chlorobenzenes, and other hazardous materials, into the old Love Canal. The disposal continued until 1952, at which time the company covered the site with soil and deeded it to the city of Niagara Falls, which wanted to use it for a public park. In transferring the deed, Hooker specifically stated that the site had been used for the burial of hazardous materials and warned the city that this fact should govern future decisions on use of the land. Everything Hooker Chemical did during those years appears to have been legal and aboveboard.

About this time, the Niagara Falls board of education was about to construct a new elementary school, and the old Love Canal seemed a perfect spot. This area was part of a growing suburb, with densely packed single-family residences on streets paralleling the old canal. A school on this site seemed like a perfect solution, so it was built.

In the 1960s the first complaints began, and they intensified during the early 1970s. The groundwater table rose during those years and brought to the surface some of the buried chemicals. Children in the school playground were seen playing with strange 55-gallon drums that popped up out of the ground. The contaminated liquids started to ooze into the basements of nearby residents, causing odor and reports of health problems. More important perhaps, the contaminated liquid was found to have entered the storm sewers and was being discharged upstream of the water intake for the Niagara Falls water treatment plant.

The situation reached a crisis point and President Jimmy Carter declared an environmental emergency in 1978, resulting in the evacuation of 950 families in an area of 10 square blocks around the canal. But the solution presented a difficult engineering problem. Excavating the waste would have been dangerous work and would probably have caused the death of some of the workers. Digging up the waste would also have exposed it to the atmosphere, resulting in uncontrolled toxic air emissions. Finally, there was the question as to what would be done with the extracted waste. Since it was mixed, no single solution such as incineration would have been appropriate. The U.S. Environmental Protection Agency (EPA) finally decided that the only thing to be done with this dump was to isolate it and continue to monitor and treat the groundwater. The contaminated soil on the school site was excavated, detoxified, and stabilized and the building was razed. All the sewers were cleaned, removing 62,000 tons of sediment that had to be treated and removed to a remote site. At the present time, the groundwater is still being pumped and treated, thus preventing further contamination.

The cost is staggering, and a final accounting is still not available. Occidental Chemical paid $129 million and continues to pay for oversight and monitoring. The rest of the funds are from the Federal Emergency Management Agency and from the U.S. Army, which was found to have contributed waste to the canal.

Cleaning Up Messes

International and domestic agencies have established sets of steps to determine the potential for a release of contaminants from a waste site. In the United States, the steps shown in Figure B3.2 comprise the Superfund cleanup process because they have been developed as regulations under the Comprehensive Environmental Response, Compensation and Liability Act, more popularly known as Superfund. The first step in this process is a preliminary assessment and site inspection, from which the site is ranked in the agency's hazard ranking system (HRS). The HRS is a process that screens the threats of each site to determine if the site should be listed on the national priority listing (NPL), which is a list of sites identified as requiring possible long-term cleanup and what the rank of a listed site should be. Following the initial investigation, a formal remedial investigation/feasibility study (RI/FS) is conducted to assess the nature and extent of contamination. The next formal step is the record of decision, which describes possible alternatives for cleanup to be used at an NPL site. Next, a remedial design/remedial action (RD/RA) plan is prepared and implemented. The RD/RA specifies which remedies will be undertaken at the site and lays out all plans for meeting cleanup standards for all environmental media. The construction completion step identifies the activities that were completed to achieve cleanup. After completion of all actions identified in the RD/RA, a program for operation and maintenance is carried out to ensure that all actions are as effective as expected and that the measures are operating properly and according to the plan. Finally, after cleanup and demonstrated success, the site may be deleted from the NPL. Note that this process closely resembles the step-wise design model described in Chapter 1.

In the first step in the process, the location of the site and boundaries should be clearly specified, including the formal address and geodetic coordinates. The history of the site, including present and all past owners and operators, should be documented. The search for this background information should include both formal (e.g., public records) and informal documentation (e.g., newspapers and discussions with neighborhood groups*). The main or most recent businesses that have operated on the site, as well as any ancillary or previous interests, should be documented and investigated. For example, in the infamous Times Beach, Missouri, dioxin contamination incident, the operator's main business was an oiling operation to control dust and to pave roads. Unfortunately, the operator also ran an ancillary waste-oil hauling and disposal business. The operator "creatively" merged these two businesses: spraying waste oil that had been contaminated with dioxins, which led to widespread pollution resulting in numerous Superfund sites in Missouri, including relocation of the entire town of Times Beach.

*Many community resources are available, from formal public meetings held by governmental authorities to informal groups, such as homeowner association meetings and neighborhood "watch" and crime prevention group meetings. Any investigation activities should adhere to federal and other governmental regulations regarding privacy, intrusion, and human subjects considerations. Privacy rules have been written according to the Privacy Act and the Paperwork Reduction Act (e.g., the Office of Management and Budget limits the type and amount of information that U.S. agencies may collect in what is referred to as an information collection budget). Any research that affects human subjects should at a minimum, have prior approval for informed consent of participants and thoughtful consideration of the need for an institutional review board approval.

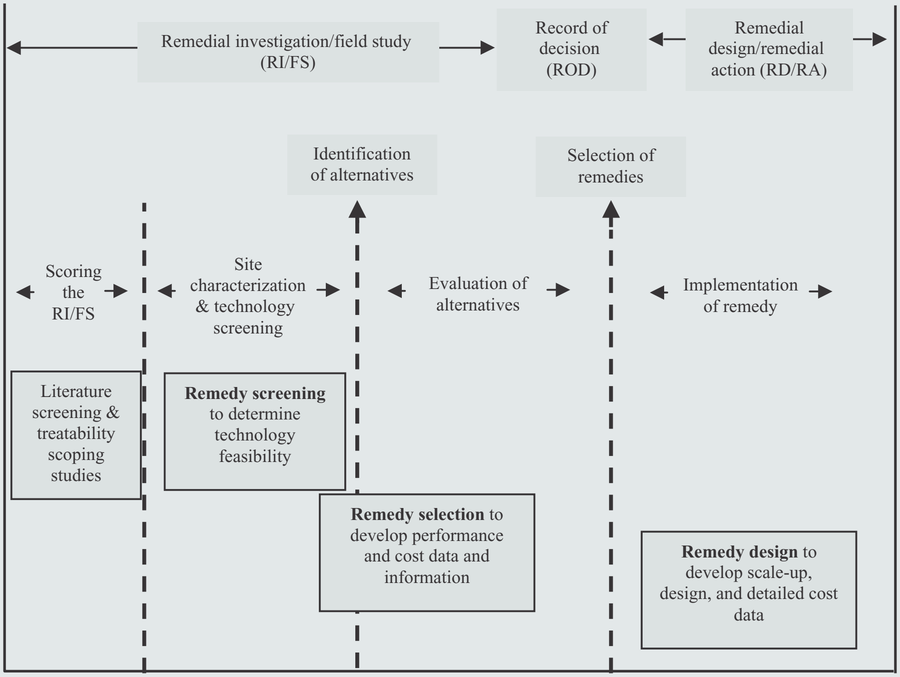


Figure B3.2 Steps in a contaminated site cleanup, as mandated by Superfund.

From U.S. Environmental Protection Agency, "Guide for conducting treatability studies under CERCLA: thermal desorption," EPA/540/R-92/074 B. U.S. EPA, Washington, DC, 1992.

The investigation at this point should include *all* past and present owners and operators. Any decisions regarding *de minimus* interests will be made at a later time (by government agencies and attorneys). Early in the process, one should be searching for every potentially responsible party. A particularly important part of this review is to document all sales of the property or any parts of the property. Also, all commercial, manufacturing, and transportation concerns should be known, as these may indicate the types of wastes that have been generated or handled at the site. Even an interest of short duration can be very important if this interest produced highly persistent and toxic substances that may still be on-site or that may have migrated off-site. The investigation should also determine whether any attempts were made to dispose of wastes from operations, either on-site or, through manifest reports, whether any wastes were shipped off-site. A detailed account should be given of all waste reporting, including air emission and water discharge permits, and voluntary audits that include tests such as the toxicity characteristic leaching procedure (TCLP), and these results compared to benchmark levels, especially to determine if any of the concentrations of contaminants exceed the U.S. EPA hazardous waste limit (40 CFR 261). For example, the TLCP limit for lead is 5 mg L^{-1}. Any exceedence of this federal limit in the soil or sand on a site must be reported.

Initial monitoring and chemical testing should be conducted to target those contaminants that may have resulted from a spill or dumping. More general surveillance is also needed to identify a broader suite of contaminants. This is particularly important in soil and groundwater, since their rates of migration are quite slow compared to the rates usually found in air and surface water transport. Thus, the likelihood of finding remnant compounds is greater in soil and in groundwater. Also, in addition to parent chemical compounds, chemical degradation products should be targeted, since decades may have passed since the waste was buried, spilled, or released into the environment. The originally released chemicals may have degraded, but their breakdown products may remain; many of which can be as toxic or more toxic than the parent substance. For example, the fungicide vivelozolin may break down readily if certain conditions and microbial populations are present in the soil. However, its toxic byproducts butenoic acid and dichloroanaline can remain.

An important part of the preliminary investigation is the identification of possible exposure, both human and environmental. For example, the investigation should document the proximity of a site to schools, parks, water supplies, residential neighborhoods, shopping areas, and businesses.

One means of efficiently implementing a hazardous waste remedial plan is for the present owners (and also past owners, for that matter) to work voluntarily with government health and environmental agencies. States often have voluntary action programs that can be an effective means of expediting the process, which allows companies to participate in, and even lead, the RI/FS consistent with a state-approved work plan (which can be drafted by the state's consulting engineer).

The feasibility study delineates potential remedial alternatives, comparing the cost-effectiveness to assess each alternative approach's ability to mitigate potential risks associated with the contamination. The feasibility study includes a field assessment to retrieve and chemically analyze (at a state-approved laboratory) water and soil samples from all environmental media on the site. Soil and vadose-zone* contamination will probably require that test pits be excavated to determine the type and extent of contamination. Samples from the pit are collected for laboratory analysis to determine general chemical composition (e.g., in a *total analyte list*) and TCLP levels (which indicate the rate of *leaching*, i.e., movement of the contaminants).

An iterative approach may be appropriate as the data are derived. For example, if the results of the screening (e.g., total analytical tests) and leaching tests indicate that a site's main problem is with one or just a few contaminants, a more focused approach to cleanup may be in order. For example, if preliminary investigation indicated that for most of the site's history a metal foundry was in operation, the first focus should be on metals. If no other contaminants are identified in the subsequent investigation, a remedial action that best contains metals may be in order. If a clay layer is identified at the site from test pit activities and extends laterally beneath the foundry's more porous overburden material, the clay layer should be sampled to see if any screening levels have been exceeded. If groundwater has not found beneath the metal-laden material, an appropriate interim action removal may be appropriate, followed by a metal treatment process for any soil or environmental media laden with metal wastes. For example, metal-laden waste has recently been treated by applying a buffered phosphate and stabilizing chemicals to inhibit lead leaching and migration. The technologies for in situ treatment are advancing rapidly.

During and after remediation, water and soil environmental performance standards must be met, confirmed by sampling and analysis: poststabilization sampling and TCLP analytical methods to assess contaminant leaching (e.g., to ensure that concentrations of heavy metals and organics do not violate federal standards: lead concentrations <5 mg L^{-1}). Confirmation samples must be analyzed to verify complete removal of contaminated soil and media in the lateral and vertical extent within the site.

The remediation steps should be delineated clearly in the final plan for remedial action, such as the total surface area of the site to be cleaned up, depth of soil to be removed, and the total volume of waste to be decontaminated. At a minimum a remedial action is evaluated on the basis of the current and proposed land use around the site; applicable local, state, and federal laws and regulations; and a risk assessment that specifically addresses the hazards and possible exposures at or near the site. Any plan proposed should summarize the environmental assessment and the potential risks to public health and the environment posed by the site. The plan should clearly delineate all remedial alternatives that have been considered. It should also include data and information on the background and history of the property, the results of previous investigations, and the objectives of remedial actions. Since this is an official document, the state environmental agency must abide by federal and state requirements for public notice as well as providing a sufficient public comment period (about 20 days).

The final plan must address all comments. The final plan of remedial action must clearly designate the remedial action selected, which will include the

*The vadose zone, also known as the unsaturated zone, is the underground layers above the water table that may contain water around soil or unconsolidated material particles, but which also contains air. Thus, unlike the zone of saturation, its void spaces are not completely filled with water.

target cleanup values for the contaminants as well as all monitoring that will be undertaken during and after the remediation. It must include both quantitative (e.g., action to mitigate risks posed by metal-laden material with total lead concentration > 1000 mg kg^{-1} and TCLP lead ≥ 5.0 mg L^{-1}) and qualitative objectives (e.g., control measures and management to ensure limited exposures during cleanup). The plan should include a discussion of planned and potential uses of the site following remediation (e.g., whether it will be zoned for industrial use or changed to another land use). The plan should distinguish between interim and final actions, as well as interim and final cleanup standards. The proposed plan and the final plan constitute the *remedial decision record*. The ultimate goal of the remediation is to ensure that all hazardous material on the site has either been removed or rendered nonhazardous through treatment and stabilization. The nonhazardous stabilized material can then be disposed of properly: for example, in a nonhazardous waste landfill. For example, a removal action is one where contaminated materials are taken away, whereas a remediation action is one where the containmation is treated to allow for a particular use. Therefore, the removal may be much less protective. than the remediation (e.g., a removal cleanup target may have a target risk $= 10^{-8}$, whereas a remediation target risk $= 10^{-6}$).

The Love Canal story had the effect of galvanizing the American public into understanding the problems of hazardous waste and was the impetus for the passage of several significant pieces of legislation, such as the Resource Conservation and Recovery Act; the Comprehensive Environmental Response, Compensation, and Liability Act; and the Toxic Substances Control Act. In particular, a new approach to assessing and addressing these problems has evolved (see the discussion box “Cleaning Up Messes”).

Love Canal is also a lesson in the need to consider cumulative and long-term effects. Each of the decisions made by the various entities may not have seemed to have been significant, but considered from a life cycle and comprehensive perspective, the results could have been predicted.

Sidebar: Applying the Synthovation/Regenerative Model: Brownfields

As mentioned, Hazardous waste cleanup has almost exclusively followed a stepwise process (see Fig. B3.2). One point that we remind our students about continuously is that regulations and laws are constraints that must not be violated in a design (even if it seems that there are more efficient and effective ways outside the bounds of law). Design professionals do not have the prerogative to ignore codes. However, recently, governments have encouraged innovation and are increasingly offering incentives in the form of tax relief to those willing to reinvest and bring abandoned properties back into productive use. These incentives include the waiving of property taxes for a number of years to allow recovery of the cleanup costs and protection from future litigation associated with the contaminated property.

In the summer of 2004, the U.S. Conference of Mayors announced a joint effort with Cherokee Investment Partners (Cherokee) to fast-track the cleanup of contaminated properties by providing access to the expertise and resources that many cities and towns lack. Cherokee, headquartered in Raleigh, North Carolina, began acquiring contaminated real estate in 1990 and has since acquired over 300 properties in the United States and Western Europe and has begun the process of transforming these brownfield properties from a community albatross to a source of economic stimulus for redevelopment. In addition to the rehabilitation of once environmentally damaged sites, development of these sites also serves to reduce the pressure on undeveloped land, preserving natural areas that provide habitat and promote biodiversity.

Admittedly, cleanup has been based strongly in chemistry. We have looked for ways to make contaminants less toxic. New thinking must be more biological. We must emulate nature. See the next sidebar on living machines.

Sidebar: Applying the Synthovation/Regenerative Model: Living Machines

Compost is very useful. Not too long ago, much of what is now compost was considered solid waste. However, as shown in Figure 3.16, compost can be used as a renewable substrate for beneficial microbes. The lesson here is that when designing buildings and developments, it is quite possible to think about by-products of human habitation as not always being wastes but sometimes being valuable resources. We can harvest these resources on-site and use them there.

The *living machine* built into the Lewis Environmental Studies Center at Oberlin College demonstrates application of the concept "waste equals food" and the ability to create a continuous regenerative cycle (Fig. S3.1). Wastewater enters the living machine system and is treated by biological organisms that break down the wastewater into nutrients, which are then fed into an adjoining constructed wetland. The process is accomplished by use of anaerobic and aerobic tanks housing bacteria that consume the pathogens, carbon, and other nutrients in a process that cleanses the water. This seems similar to biological treatment at the municipal wastewater facility. However, as Kibert notes in *Sustainable Construction*, a living machine differs from a conventional wastewater

Figure S3.1 Living machine.

Courtesy of DOE/NREL, photo by Robb Williamson, NREL Pix #10871.

treatment plant in four basic respects*:

1. The vast majority of a living machine's working parts are living organisms. Like the treatment plant, bacteria are involved, but a living machine includes hundreds of species of bacteria, plants, and vertebrates such as fish and reptiles. That is, it is a regenerative and diverse system.
2. A living machine has the ability to self-design its internal ecology in relation to the energy and nutrient streams to which it is exposed. That is, it is an adaptive system.
3. A living machine can self-repair when damaged by toxics or when shocked by interruption of energy or nutrient sources. That is, it is a resilient and elastic system.
4. A living machine can self-replicate through reproduction by the organisms in the system. That is, it is a sustainable system.

*Kilbert, *Sustainable Construction*, Wiley, Hoboken, NJ.

THE BHOPAL INCIDENT

No case illustrates the need for green engineering principles in every design better than the chemical accident at Bhopal, India. No designer wants to read a newspaper account such as the following about one's project:

> In the middle of the night of December 2–3, 1984, residents living near the Union Carbide pesticide plant in Bhopal, India awoke coughing, choking, gasping, and in the case of thousands, slowly dying. Half a day later, half a world away, company executives sleeping soundly near the Danbury, CT headquarters of Union Carbide Corporation awoke in the middle of the night yawning and grumbling at the sound of telephones ringing. . . . Shortcuts taken in the name of profit—authorized by the highest executives within the company—had just killed thousands of innocent citizens. It was the worst industrial disaster of the 20th century, forever changing the public's trust of the chemical industry. Union Carbide claimed it was sabotage by a disgruntled employee that led to the disaster, but how much did the company already know about the dangerous conditions its shortcuts and bottom-line focus had created?[5]

Among the largest air pollution disasters of all time occurred in Bhopal, in 1984 when a toxic cloud drifted over the city from the Union Carbide pesticide plant. This gas leak led to the death of 20,000 people and the permanent injury of 120,000 others. We often talk about a failure that results from not applying the sciences correctly (e.g., a mathematical, error, an incorrect extrapolation of a physical principle). Another type of failure results from misjudgments of human factors. Bhopal had both.

Although the Union Carbide Company was headquartered in the United States, as of 1984 it operated in 38 countries. It was quite large (the thirty-fifth-largest U.S. company) and was involved in numerous types of manufacturing, most of which involved proprietary chemical processes. The pesticide manufacturing plant in Bhopal had produced the insecticides Sevin and Cararyl since 1969, using the intermediate product methyl isocyanate (MIC) in its gas phase. The MIC was produced by the reaction shown in Figure 3.4.[6] This process

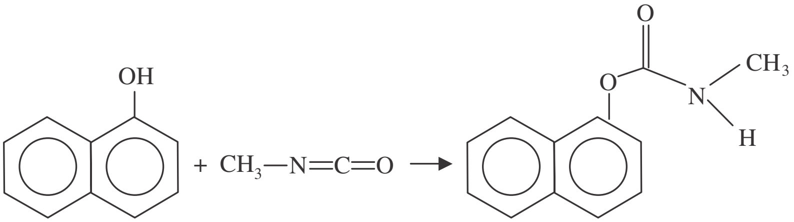


Figure 3.4 Chemical reaction producing methyl isocyanate at the Bhopal, India, Union Carbide plant.

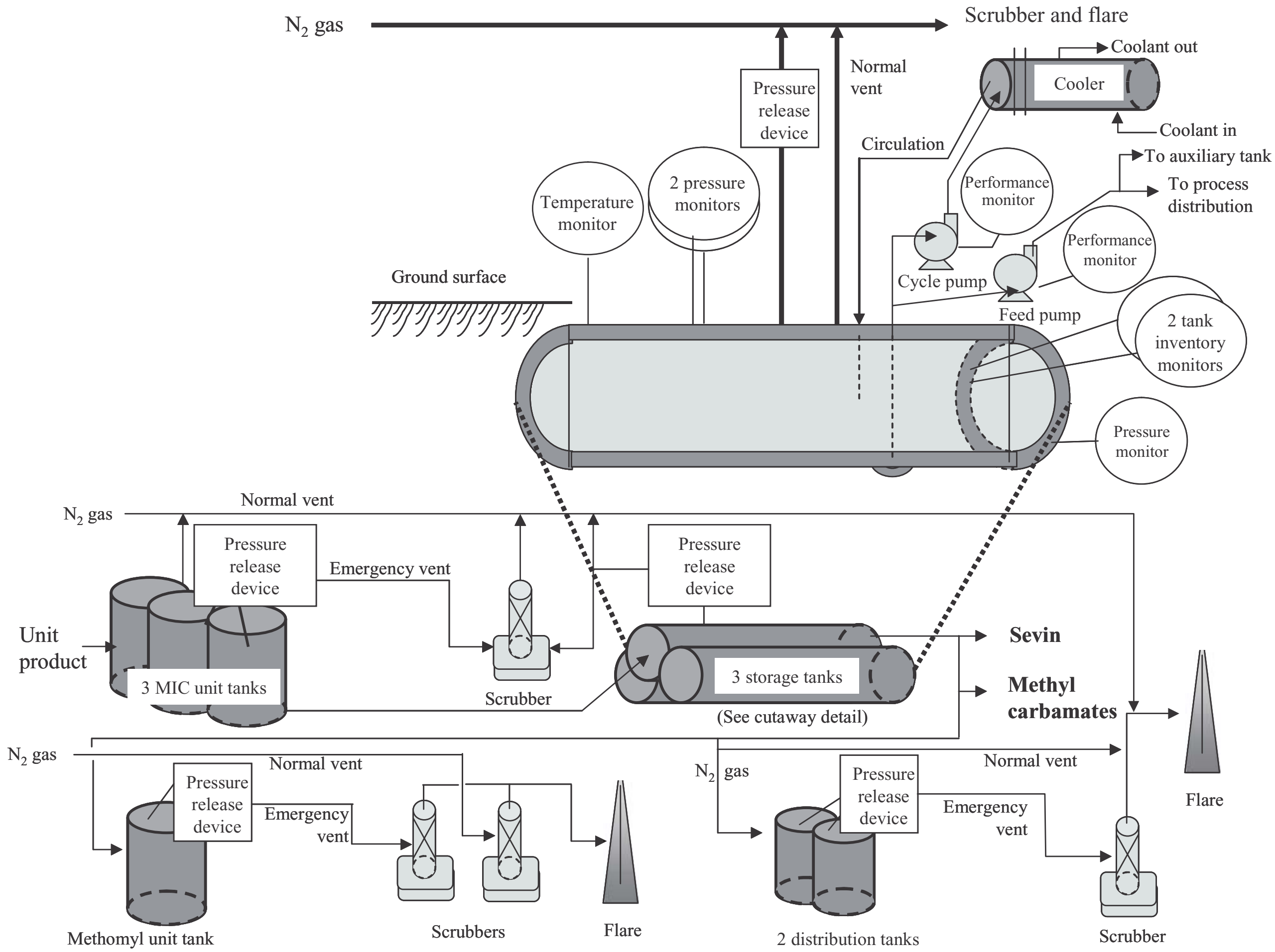


Figure 3.5 Methyl isocyanate processes at the Bhopal, India, plant circa 1984.

Adapted from W. Worthy, 1985, “Methyl isocyanate: the chemistry of a hazard,” *Chemical Engineering News*, 63(66), 29.

was highly cost-effective, involving only a single reaction step. A schematic of the MIC process in shown in Figure 3.5. MIC is highly water reactive (see Table 3.1); that is, it reacts violently with water, generating a very strong exothermic reaction that produces carbon dioxide. When MIC vaporizes, it becomes a highly toxic gas that, when concentrated, is highly caustic and burns tissues. This can lead to scalding nasal and throat passages, blinding, and loss of limbs, as well as death.

An important point can be made about the information in Table 3.1. The safety limits are based on workplace and workday scenarios (i.e., 8-hr days and 40-hr weeks). This is different, yet informative for residential building design. For example, contaminant levels should be even more protective for residential structure’s indoor occupants, since they will be potentially exposed for larger times (sometimes 24 hours per day for an entire lifetime).

Table 3.1 Properties of Methyl Isocyanate

Common names	Isocyanic acid, methylester, and methyl carbylamine
Molecular mass	57.1
Properties	Melting point: −45°C; boiling point: 43–45°C. Is a volatile liquid. Has a pungent odor. Reacts violently with water and is highly flammable. MIC vapor is denser than air and will collect and stay in low areas; the vapor mixes well with air, and explosives mixtures are formed. May polymerize due to heating or under the influence of water and catalysts. Decomposes on heating and produces toxic gases such as hydrogen cyanide, nitrogen oxides, and carbon monoxide.
Uses	Used in the production of synthetic rubber, adhesives, pesticides, and herbicide intermediates; also used for the conversion of aldoximes to nitriles.
Side effects	MIC is extremely toxic by inhalation, ingestion, and skin absorption. Inhalation of MIC causes cough, dizziness, shortness of breath, sore throat, and unconsciousness. It is corrosive to the skin and eyes. Short-term exposures also lead to death or adverse effects such as pulmonary edema (respiratory inflammation), bronchitis, bronchial pneumonia, and reproductive effects. The Occupational Safety and Health Administration's permissible exposure limit to MIC over a normal 8-hour workday or a 40-hour workweek is 0.05 mg m^{-3}.

Source: U.S. Chemical Safety and Hazards Board, http://www.chemsafety.gov/lib/bhopal.0.1.htr; *Dictionary of Organic Chemistry*, Vol. 4, 5th ed., Chapman and Hall, London, 1982; T. W Graham, *Organic Chemistry*, 6th ed., Wiley, Mississauga, Canada, 1996.

On December 3, 1984, the Bhopal plant operators became concerned that a storage tank was showing signs of overheating and began to leak. The tank contained MIC. The leak increased in size rapidly, and within one hour of the first leakage, it exploded and released approximately 80,000 lb (4×10^4 kg) of MIC into the atmosphere.

Introduction of water to the MIC storage tank resulted in a highly exothermic reaction generating CO_2, which would have led to a rapid increase in pressure, which could have caused the release of 40 metric tons of MIC into the atmosphere. The release led to arguably the worst industrial disaster on record. The human exposure to MIC was widespread, with a half million people exposed. Nearly 3000 people died within the first few days after exposure, and 10,000 people were permanently disabled. Ten years after the incident, 12,000 death claims had been filed, along with 870,000 personal injury claims. However, only $90 million of the Union Carbide settlement agreement had been paid out.

As of 2001, many victims did receive compensation, averaging about $600 each, although some claims are still outstanding. The Indian government required that the plant be operated exclusively by Indian workers, so Union Carbide agreed to train them, including flying them to a sister plant in West

Virginia for hands-on sessions. In addition, the company required that U.S. engineering teams make periodic on-site inspections for safety and quality control, but these ended in 1982, when the plant decided that these costs were too high. Instead, the U.S. contingency was responsible for budgetary and technical controls but not for safety. The last U.S. inspection in 1982 warned of many hazards, including a number that have since been implicated as contributing to the leak and release.

From 1982 to 1984, safety measures declined, which was attributed to high employee turnover, improper and inadequate training of new employees, and low technical savvy in the local workforce. On-the-job experiences were often substituted for reading and understanding safety manuals. (Remember, this was a pesticide plant.) In fact, workers would complain of typical acute symptoms of pesticide exposure, such as shortness of breath, chest pains, headaches, and vomiting, yet they would commonly refuse to wear protective clothing and equipment. The refusal in part stemmed from the lack of air conditioning in this subtropical climate, where masks and gloves can be uncomfortable. After 1982, Indian, rather than the more stringent U.S., safety standards were generally followed at the plant. This probably contributed to overloaded MIC storage tanks (company manuals cite a maximum of 60% fill).

The release lasted about two hours, after which the entire quantity of MIC had been released. The highly reactive MIC arguably could have reacted and become diluted beyond a certain safe distance. However, over the years, tens of thousands of squatters had taken up residence just outside the plant property, hoping to find work or at least to take advantage of the plant's water and electricity. The squatters were not notified of hazards and risks associated with the pesticide manufacturing operations, except by a local journalist who posted signs saying: "Poison Gas. Thousands of Workers and Millions of Citizens Are in Danger." This is a classic instance of a "confluence of events" that led to a disaster. More than a few mistakes were made. The failure analysis found the following:

- The tank that initiated the disaster was 75% full of MIC at the outset, well above the 60% maximum recommended in the safety manual.
- A standby overflow tank for the storage tank contained a large amount of MIC at the time of the incident. Overflow tanks under normal conditions should be empty.
- A required refrigeration unit for the tank had been shut down five months prior to the incident, leading to a three- to fourfold increase in tank temperatures over expected temperatures.
- One report stated that a disgruntled employee unscrewed a pressure gauge and inserted a hose into the opening (knowing that it would do damage but probably not to nearly the scale of what occurred).

- A new employee was told by a supervisor to clean out connectors to the storage tanks. The worker closed the valves properly but did not insert safety disks to prevent the valves from leaking. In fact, the worker knew the valves *were* leaking but believed that they were the responsibility of the maintenance staff. Also, the second-shift supervisor position had been eliminated, meaning one less source of safety information was available to workers.
- When the gauges started to show unsafe pressures, and even when the leaking gases started to sting the mucous membranes of workers, they found that evacuation exits were not available. There had been no emergency drills or evacuation plans.
- The primary fail-safe mechanism against leaks was a vent-gas scrubber. Normally, this release of MIC would have been sorbed and neutralized by sodium hydroxide (NaOH) in the exhaust lines, but on the day of the disaster, the scrubbers were not working. (The scrubbers were deemed unnecessary, since they had never been needed before.)
- A flare tower to burn off any escaping gas that would bypass the scrubber was not operating because a section of conduit connecting the tower to the MIC storage tank was under repair.
- Workers attempted to mediate the release by spraying water to 100 feet, but the release occurred at 120 feet.

Thus, according to the audit, many checks and balances were in place, but cultural considerations were ignored or given low priority, such as the need to recognize differences in land-use planning and buffer zones in India and in Western nations, and the differences in training and oversight of personnel in safety programs. Every engineer and environmental professional needs to recognize that much of what we do is affected by geopolitical realities, and that we work in a global economy. This means that we must understand how cultures differ in their expectations of environmental quality. One cannot assume that a model that works in one setting will necessarily work in another without adjusting for differing expectations. Bhopal demonstrated the consequences of ignoring these realities.

Smaller versions of the Bhopal incident are more likely to occur, but with more limited impacts. For example, two freight trains collided in Graniteville, South Carolina, just before 3:00 A.M. on January 6, 2005, resulting in the derailment of three tanker cars carrying chlorine (Cl_2) gas and one tanker car carrying sodium hydroxide (NaOH) liquids. The highly toxic Cl_2 gas was released to the atmosphere. The wreck and gas release resulted in hundreds of injuries and eight deaths.

In February 2005, the District of Columbia city council banned large rail shipments of hazardous chemicals through the U.S. capital, making it the first large metropolitan area in the United States to attempt to reroute trains carrying potentially dangerous materials. The CSX Railroad has opposed the restrictions, arguing that they violate constitutional protections and interstate commerce legislation and rules. While the Graniteville chlorine leak is a recent example of rail-related exposure to hazardous wastes, it is also a reminder that roads and rails are in very close contact to areas where people live. And incidents are not really that rare. Seven months before the Graniteville incident, three people died after exposure to chlorine as a result of a derailment in San Antonio, Texas; 50 people were hospitalized. Although a leading concern is occupational safety (the engineer died in the San Antonio wreck), transportation also increases community exposure. The two other deaths and most of the hospitalized were people living in the neighborhood where the leak occurred.

Many metropolitan areas also have areas where rail, trucks, and automobiles meet, so there is an increased risk of accidents. Most industrialized urban areas have a problematic mix of high-density population centers, multiple modes of transport, dense rail and road networks, and rail-to-rail and rail-to-truck exchange centers. Since they are major crossroads, most cities are especially vulnerable to an accident involving hazardous chemicals. Rerouting trains is not feasible in many regions because transcontinental lines here run through most urban areas. So other steps should be taken to reduce shipment risks from hazardous substances such as chlorine, and improvements in manifest reports would make information available immediately to first responders. At present, such information is not generally available. Following the September 11, 2001 attacks, some rail companies have been reticent to disclose what is being shipped. One local fire department spokesman has stated that one "could almost assume there are several cars of hazardous materials every time we see a train."[7]

The lessons from Bhopal Graniteville and other toxic clouds are many. However, a major one for green engineering is that impacts (i.e., artifacts) will occur downstream. That is, there can be a propagation of factors that can substantially increase the risks from an event. A number of these cannot be fully appreciated prospectively, so factors of safety must be built into the design, and human factors must always be seen as design constraints. The plan is only as good as the manner in which it is implemented. If this is sloppy, failure and, tragically, disaster may be the result.

Other important industrial accidents and events must also be added to our list, such as the mercury releases to Minamata Bay in Japan, the effect of cadmium exposure that lead to Itai Itai disease in many Japanese, and air pollution episodes in Europe and the United States. Also, new products that at first appear to be beneficial have all too often been found to be detrimental to public health and the environment.

There is little agreement on the criteria for ranking importance of environmental events. For example, death toll and disease (e.g., cancer, asthma, or waterborne pathogenic disease) are often key criteria. Also, the larger the area affected, the worse the disaster, such as the extent of an oil slick or the size of a toxic plume in the atmosphere. Even monetary and other values are used as benchmarks. Sometimes, however, timing may be the most important criterion. Even if an event does not lead to an extremely large number of deaths or diseases, or its spatial extent is not appreciably large, it may still be very important because of where and when the event occurs. For example, the contamination of Times Beach, Missouri, although affecting much of the town, was not the principal reason for the national attention. The event occurred shortly after the Love Canal hazardous waste problem was identified and people were wondering just how extensively dioxin and other persistent organic compounds were going to be found in the environment. Times Beach also occurred at a time when scientists and engineers were beginning to get a handle on how to measure and even how to treat (i.e., by incineration) contaminated soil and water. Other events also seem to have received greater attention due to their timing, such as the worries about DDT and its effect on eagles and other wildlife, *Cryptosporidium* outbreaks, and Legionnaire's disease.

Some environmental incidents are not well defined temporarily but are important because of the pollutants themselves. One would be hard pressed to identify a single event that caused the public concern about lead. In fact, numerous incremental steps brought the world to appreciate lead toxicity and risk. For example, studies following lead reductions in gasoline and paint showed marked improvements in blood lead levels in many children. Meanwhile, scientific and medical research was linking lead to numerous neurotoxic effects in the peripheral and central nervous systems, especially of children. Similar, stepwise progressions of knowledge of environmental risk occurred for polychlorinated biphenyls (PCBs), numerous organochlorine, organophosphate, and other pesticides, depletion of the stratospheric ozone layer by halogenated (especially chlorinated) compounds, and even the effect of releases of carbon dioxide, methane, and other "greenhouse gases" on global warming (called more properly, *global climate change*).

CONTROL

Engineers and other design professionals are control freaks—this is necessary. Design professionals are held accountable for the success of any design: congratulated when it succeeds and blamed when it fails.

Like almost everything else in environmental protection, new systematic approaches call for new terms (and new acronyms). In green engineering and sustainable design, these are design for the environment (DFE), design for disassembly (DFD), and design for recycling (DFR).[8] For example, the concept of a *cap and trade* has been tested and works well for some pollutants and has elements of DFE, DFD, and DFR. This is a system whereby companies are allowed to place a "bubble" over an entire manufacturing complex or allowed to trade pollution credits with other companies in their industry instead of a "stack-by-stack" and "pipe-by-pipe" approach (i.e., called the *command and control approach*). Such policy and regulatory innovations call for some improved technology-based approaches as well as better quality-based approaches, such as leveling out the pollutant loadings and using less expensive technologies to remove the first large bulk of pollutants, followed by more effective operation and maintenance technologies for the more difficult-to-treat stacks and pipes. But the net effect can be a greater reduction of pollutant emissions and effluents than that obtained by treating each stack or pipe as an independent entity. This is a foundation for most sustainable design approaches: conducting a life-cycle analysis, prioritizing the most important problems, and matching the technologies and operations to address them. The problems will vary by size (e.g., pollutant loading), difficulty in treating, and feasibility. The easiest ones are the big ones that are easy to treat (so-called "low-hanging fruit"). You can do these first with immediate gratification! However, the most intractable problems are often those that are small but very expensive and difficult to treat (i.e., less feasible). Thus, green thinking requires that expectations be managed from both a technical and an operational perspective, including the expectations of the client, the government, and oneself.

Green engineering is not limited to preventing problems but can also be applied to solving those that already exist. Pollution control strategies must complement control technologies with pollution prevention. Pollution controls are a necessary part of modern engineering. Power plants have electrostatic precipitators and scrubbers, large cities and small towns build and maintain wastewater treatment plants, groundwater cleanup from hazardous wastes is ubiquitous, military operations have left contaminated soils that must be remediated, and radioactive wastes remain after weapons manufacturing and energy production. Environmental engineering continues to evolve and to find ways to collect and treat myriad contaminants, which in turn reduces the impact of these substances on public health and ecological conditions. Engineers, biologists, and other scientists also work to reduce the overall toxicity of waste, to decrease exposures, and ultimately, to eliminate or at least to treat properly the risks from hazardous substances in the waste.

The type of pollution control technology applied depends on the intrinsic characteristics of the contaminants and the substrate in which they reside. The choice must factor in all of the physical, chemical, and biological characteristics of the contaminant with respect to the matrices and substrates (if soil and sediment) or fluids (air, water, or other solvents) where the contaminants are found. The approach selected must meet criteria for treatability (i.e., the efficiency and effectiveness of a technique in reducing the mobility and toxicity of a waste). The comprehensive remedy must consider the effects that each action taken will have on past and future steps.

Table 3.2 Effect of the Characteristics of the Contaminant on Decontamination Efficiencies[a]

	Organic Contaminants					Inorganic Contaminants		
Treatment Technology	PCBs	PAHs	Pesticides	Petroleum Hydrocarbons	Phenolic Compounds	Cyanide	Mercury	Other Heavy Metals
Conventional incineration	D	D	D	D	D	D	xR	pR
Innovative incineration[b]	D	D	D	D	D	D	xR	I
Pyrolysis[b]	D	D	D	D	D	D	xR	I
Vitrification[b]	D	D	D	D	D	D	xR	I
Supercritical water oxidation	D	D	D	D	D	D	U	U
Wut air oxidation	pD	D	U	D	D	D	U	U
Thermal desorption	R	R	R	R	U	U	xR	N
Immobilisation	pI	pI	pI	pI	pI	pI	U	I
Solvent extraction	R	R	R	R	R	pR	N	N
Soil washing[c]	pR	pR	pR	pR	pR	pR	pR	pR
Dechlorination	D	N	pD	N	N	N	N	N
Oxidation[d]	N/D	N/D	N/D	N/D	N/D	N/D	U	XN
Bioremediation[e]	N/pD	N/D	N/D	D	D	N/D	N	N

[a] PCBs, polychlorinated biphenyls; PAHs, polynuclear aromatic hydrocarbons; D, effectively destroys contaminant; R, effectively removes contaminant; I, effectively immobilizes contaminant; N, no significant effect; N/D, effectiveness varies from no effect to highly efficient, depending on the type of contaminant within each class; U, effect not known; P, partial; X, may cause release of nontarget contaminant.

[b] This process is assumed to produce a vitrified slag.

[c] The effectiveness of soil washing is highly dependent on the particle size of the dediment matrix, contaminant characteristics, and the type of extractive agents used.

[d] The effectiveness of oxidation depends strongly on the types of oxidant(s) involved and the target contaminants.

[e] The effectiveness of bioremediation is controlled by a large number of variables, as discussed in the text.

(*Source*: U.S. Environmental Protection Agency, Remediation Guidance Document, EPA-905-B94-003, Chapter 7, U.S. EPA, Washington, DC, 2003.)

A word of warning: The policy and scientific inertia of the events of the twentieth century led to a viewpoint that problems and events can be grouped by media (i.e., air, water, and land). Agencies are structured around this view. However, such thinking is wholly inconsistent with integrative, green solutions. Green design requires an appreciation for the interactions within and between environmental media. As mentioned in Chapter 2, if we let the thermodynamics dictate our thinking, we can begin to approach environmental problems from a multimedia, multicompartmental perspective, allowing the designer to consider the properties and behavior of the principal environmental fluids, especially air and water.

Eliminating or reducing pollutant concentrations begins with assessing the physical and chemical characteristics of each contaminant and matching these characteristics with the appropriate treatment technology. All of the kinetics and equilibria, such as chemical degradation rates, solubility, fugacity, sorption, and bioaccumulation factors, will determine the effectiveness of destruction, transformation, removal, and immobilization of these contaminants. For example, Table 3.2 ranks the effectiveness of selected treatment technologies on organic and inorganic contaminants typically found in contaminated slurries, soils, sludges,

Table 3.3 Effect of Particle Size, Solids Content, and Extent of Contamination on Decontamination Efficiencies[a]

	Predominant Panicle Size			Solids Content		High Contaminant Concentration	
Treatment Technology	Sand	Silt	Clay	High (slurry)	Low (in situ)	Organic Compounds	Metals
Conventional incineration	N	X	X	F	X	F	X
Innovative incineration	N	X	X	F	X	F	F
Pyrolysis	N	N	N	F	X	F	F
Vitrification	F	X	X	F	X	F	F
Supercritical water oxidation	X	F	F	X	F	F	X
Wut air oxidation	X	F	F	X	F	F	X
Thermal desorption	F	X	X	F	X	F	N
Immobilisation	F	X	X	F	X	X	N
Solvent extraction	F	F	X	F	X	X	N
Soil washing	F	F	X	N	F	N	N
Dechlorination	U	U	U	F	X	X	N
Oxidation	F	X	X	N	F	X	X
Bioslurry process	N	F	N	N	F	X	X
Composting	F	N	X	F	X	F	X
Contained treatment facility	F	N	X	F	X	X	X

[a] F, sediment characteristic favorable to the effectiveness of the process; N, sediment characteristic has no significant effect on process performance; U, effect of sediment characteristic on process is unknown; X, sediment characteristic may impede process performance or increase cost.

Source: U.S. Environmental Protection Agency, Remediation Guidance Document, EPA-905-B94-003, Chapter 7, U.S. EPA Washington, DC, 2003.

and sediments. As shown, there can be synergies (e.g., innovative incineration approaches are available that not only effectively destroy organic contaminants, but in the process also destroy the inorganic cyanic compounds).

Unfortunately, there are also antagonisms among certain approaches, such as the very effective incineration processes for organic contaminants that transform heavy metal species into more toxic and more mobile forms. The increased pressures and temperatures are good for breaking apart organic molecules and removing functional groups that lend them toxicity, but these same factors oxidize or in other ways transform the metals into more dangerous forms. So when mixtures of organic and inorganic contaminants are targeted, more than one technology may be required to accomplish project objectives, and care must be taken not to trade one problem (e.g., destruction of PCBs) for another (e.g., creation of more-mobile species of cadmium).

The characteristics of the soil, sediment, or water will affect the performance of any contaminant treatment or control. For example, sediment, sludge, slurries, and soil characteristics that will influence the efficacy of treatment technologies include particle size, solids content, and high contaminant concentration (see Table 3.3). Of course, the underlying assumption of this book is that the most effective approach is to avoid producing the contamination in the first place. A factor as specific and seemingly mundane as particle size may be the most important limiting characteristic for application of treatment technologies to certain wastes (e.g., contaminated sediments). It reminds us that green designs are only as good as their attention to minute details. Looking at the tables, we see the peril of "one size fits all" thinking. Most treatment technologies work well on sandy soils and sediments. The presence of fine-grained material adversely affects treatment system emission controls because it increases particulate generation during thermal drying, it is more difficult to dewater, and it has greater attraction to the contaminants (particularly, clays). Clayey sediments that are cohesive also present material-handling problems in most processing systems. The solids content generally ranges from high [i.e., usually the in situ solids content (30 to 60% solids by weight)] to low [e.g., hydraulically dredged sediments (10 to 30% solids by weight)]. Treatment of slurries is better for lower solids contents, but this can be achieved even for high solids contents by water addition at the time of processing. It is more difficult to change a lower to a higher solids content, but evaporative and dewatering approaches, such as those used for municipal sludges, may be employed. Also, thermal and dehalogenation processes are decreasingly efficient as solids content is reduced. More water means increased chemical costs and increased need for wastewater treatment.

We must be familiar with every potential contaminant in the life cycle. We must understand how it is generated and how it changes in space and time. Again, a quick review of the tables shows that elevated levels of organic compounds or heavy metals in high concentrations can be drivers in deciding on the appropriate technological and operational solution but also as indicators or possible ways to prevent pollution. Higher total organic carbon (TOC) contents favor incineration and oxidation processes. The TOC can be the contaminant of concern or any organic, since they are combustibles with caloric value. Conversely, higher metal concentrations may make a technology less favorable by increasing the contaminant mobility of certain metal species following application of the technology.

A number of other factors may affect the selection of a treatment technology in ways other than its effectiveness for treatment (some are listed in Table 3.4). For example, vitrification and supercritical water oxidation have been used only for relatively small projects and would require more of a proven track record before being implemented for full-scale sediment projects. Regulatory compliance and community perception are always a part of decisions regarding an incineration system. Land-use considerations, including the amount of acreage needed, are commonly confronted in solidification and solid-phase bioremediation projects (as they are in sludge farming and land application). Disposing of ash and other residues following treatment must be part of any process. Treating water effluent and air emissions must be part of the decontamination decision-making process.

Table 3.4 Critical Factors in the Choice of Decontamination and Treatment Approaches

Treatment Technology	Imptementabilily at Full Scale	Regulatory Compliance	Community Acceptance	Land Requirements	Residuals Disposal	Wastewater Treatment	Air Emissions Control
Conventional incineration		X	X				X
Innovative incineration		X	X				X
Pyrolysis		X					X
Vitrification	X	X					X
Supercritical water oxidation	X						
Wet air oxidation							
Thermal desorption					X	X	X
Immobilization				X			X
Solvent extraction					X	X	
Soil washing					X	X	
Dechlonnation							X
Oxidation	X						
Bioslurry process	X						X
Composting				X			X
Contained treatmont facility				X		X	X

Source: U.S. Environmental Protection Agency, Remediation Guidance Document, EPA-905-B94-003, Chapter 7, U.S. EPA, Washington, DC, 2003.

The job is not finished until these and other life cycle considerations are factored into the design.

Indeed, a good design must account for the entire life cycle of a potential hazard. For example, we must concern ourselves not only about the processes over which we have complete control, such as the manufacturing design process for a product or the treatment of a waste within the company's property lines but must also think about what happens when a chemical or other stressor enters the environment.[9] We must be able to show how a potential contaminant moves after entering the environment, which is complicated and difficult because there is much variability of chemical and physical characteristics of contaminated media (especially soils and sediments), owing to the strong affinity of most contaminants for fine-grained sediment particles and due to the limited track record or "scale-up" studies for many treatment technologies. Off-the-shelf models can be used for simple process operations, such as extraction or thermal vaporization applied to single contaminants in relatively pure systems. However, such models have not been evaluated appropriately for a number of other technologies because of the limited database on treatment technologies, such as for contaminated sediments or soils.

Standard engineering practice[10] for evaluating the effectiveness of treatment technologies for any type of contaminated media (solids, liquids, or gases) requires first performing a treatability study for a sample that is representative of the contaminated material. The performance data from treatability studies can aid in

Table 3.5 Selected Waste Streams Commonly Requiring Treatability Studies

	Treatment Technology Type						
Contaminant Loss Stream	Biological	Chemical	Extraction	Thermal Desorption	Thermal Destruction	Immobilization	Particle Separation
Residual solids	X	X	X	X	X	X	X
Wastewater	X	X	X	X			X
Oil/organic compounds			X	X			X
Leachate						X[a]	
Stack gas				X	X		
Adsorption media			X	X			
Scrubber water					X		
Particulates (filter/cyclone)				X	X		

[a] Long term contaminant losses must be estimated using leaching tests and contaminant transport modeling similar to that used for sediment placed in a confined disposal facility. Leaching could be important for residual solids for other processes as well.

Source: U.S. Environmental Protection Agency, Remediation Guidance Document, EPA-905-B94-003, Chapter 7, U.S. EPA, Washington, DC, 2003.

reliably estimating contaminant concentrations for the residues that remain after treatment, as well as possible waste streams that could be generated by applying a given technology. Treatability studies may be performed at the bench scale (in the lab) or pilot scale (e.g., a real-world study but limited in the number of contaminants, in spatial extent, or to a specific highly controlled form of a contaminant such as one pure congener of PCBs rather than the common mixtures). Most treatment technologies include post-treatment or controls for waste streams produced by processing. The contaminant losses can be defined as the residual contaminant concentrations in the liquid or gaseous streams released to the environment. For technologies that extract or separate the contaminants from the bulk of the sediment, a concentrated waste stream may be produced that requires treatment off-site at a hazardous waste treatment facility, where permit requirements may require destruction and removal efficiencies greater than 99.9999% (called the *rule of six nines*). The other source of loss for treatment technologies is the residual contamination in the sediment after treatment. After disposal, treated wastes are subject to leaching, volatilization, and losses by other pathways. The significance of these pathways depends on the type and level of contamination that is not removed or treated by the treatment process. Various waste streams for each type of technology that should be considered in treatability evaluations are listed in Table 3.5.

This life-cycle view also is the first step toward preventing problems. For example, if we consider all possible contaminants of concern, we can compare which must be avoided completely, which are acceptable with appropriate safeguards and controls, and which are likely to present hazards beyond our span of control. We may also ascertain certain processes that generate none of these hazards. Obviously, this is a preferable way to prevent problems. This is a case where we would be applauded for thinking first "inside the box." We can then progress toward thinking outside the box, or better yet in some cases, getting rid of the box completely by focusing on function rather than processes.

AD HOC AND *POST HOC* LIFE-CYCLE PERSPECTIVES

The same life-cycle viewpoint so important to waste audits, environmental management systems, and green engineering is also valuable in controlling pollutants after they are released. Five steps in sequence define an event that results in environmental contamination of the air, water, or soil pollution. These steps individually and collectively offer opportunities to intervene and to control the risks associated with hazards and thus protect public health and the environment. The steps address the presence of waste at five points in the life cycle:

Source →
Release →
Transport →
Exposure →
Response

As a first step, the contaminant source must be identifiable. A hazardous substance must be released from the source; be transported through the water, air, or soil environment; reach a human, animal, or plant receptor in a measurable dose; and the receptor must have a quantifiable detrimental response in the form of death or illness. Intervention can occur at any one of these steps to control the risks to public health and to the environment. Of course, any intervention scheme and subsequent control by the engineer must be justified by the designer as well as by the public or private client in terms of scientific evidence, sound engineering design, technological practicality, economic realities, ethical considerations, and the laws of local, state, and national governments. As a reminder, the intervention would be wholly unnecessary if the contaminant did not exist. Thus, intervention is a response to an inherited problem; one that could have been prevented.

Intervention at the Source of Contamination

A contaminant must be identifiable, either in the form of an industrial facility that generates waste by-products, a hazardous waste-processing facility, a surface or subsurface land storage/disposal facility, or an accidental spill into a water, air, or soil receiving location. The intervention must minimize or eliminate the risks to public health and the environment by utilizing technologies at this source that are economically acceptable and based on applicable scientific principles and sound engineering designs. Of course, if we are able to completely transition to an alternative green process that does not generate the waste, our job would be done.

In the case of an industrial facility producing hazardous waste as a necessary and unpreventable by-product of a profitable item, as considered here, for example, the engineer can take advantage of the growing body of knowledge that has become known as life-cycle analysis.[11] In the case of a hazardous waste storage facility or a spill, the engineer must take the source as a given and search for possibilities for intervention at a later step in the sequence of steps, as discussed below.

Under the life-cycle analysis method of intervention, the environmental manager considers the environmental impacts that could incur during the entire life cycle of (1) all of the resources that go into the product, (2) all the materials that are in the product during its use, and (3) all the materials that are available to exist from the product once it or its storage containers are no longer economically useful to society. Few simple examples exist that describe how *life cycle analysis* is conducted, but consider any of a number of household cleaning products. Consider that a particular cleaning product, a solvent of some sort, must be fabricated from one of several basic natural resources. Assume further that this cleaning product is currently petroleum based. An engineer could intervene at this initial step in the life cycle of this product, as the natural resource is being selected, and consequently, the engineer could preclude the formation of a source of hazardous waste by suggesting instead the production of a water-based solvent.

Similarly, intervention at the production phase of this product's life cycle and suggesting fabrication techniques can preclude the formation of a source of certain contaminants from the outset. In this case the recycling of spent petroleum materials could provide for more household cleaning products with less or zero hazardous waste generation, thus controlling risks to public health and the environment. Another example is that of *cogeneration*, which may allow for two manufacturing facilities to colocate so that the "waste" of one is a "resource" for the other. An example is the location of a chemical plant near a power generation facility, so that the excess steam generated by the power plant can be piped to the nearby chemical plant, obviating the need to burn its own fuel to generate the steam needed for chemical synthesis. Another example is the use of an alcohol produced from anaerobically treating a waste from one plant that is a source of a reagent or fuel for chemical processes at another.

The design process must account for possible waste streams long before any switches are flipped or valves turned. For example, a particular household cleaning product may result in unintended human exposure to buckets of solvent mixtures that fumigate the air in a home's kitchen or pollute a town's sewers as the bucket's liquid is flushed down a drain. In fact, millions of dollars are spent on pretreatment systems in municipal plants to remove such chemicals that will kill the beneficial microbes that do the work in cleaning waste-water. In this way, life-cycle analysis is a type of systems engineering where a critical path is drawn and each decision point is considered.

Using a sustainable design approach (e.g., design for the environment) requires that the disposal of this solvent's containers must be incorporated as a design constraint from a long-term risk perspective. The challenge is that every potential and actual environmental impact of a product's fabrication, use, and ultimate disposal must be considered. This is seldom, if ever, a "straight-line projection."

Intervention at the Point of Release

If the pollutant release is not completely eliminated early in the life cycle, the next step is to intervene at the point at which the waste is released into the environment. This point of release could be at the top of a stack or vent from the source of pollution to a receiving air shed, or it could be a more indirect release, such as from the bottommost layer of a clay liner in a hazardous waste landfill connected to surrounding soil material. Similarly, this point of release could be a series of points as a contaminant is released along a shoreline from a plot of land into a river or through a plane of soil underlying a storage facility (i.e., called *nonpoint source*).

Intervention as a Contaminant Is Transported in the Environment

Wise site selection of facilities actually occurs early in the life cycle. For facilities that generate, process, and store contaminants it is the first step in preventing or reducing the likelihood that pollutants will move. For example, the distance from a source to a receptor is a crucial factor in controlling the quantity and characteristics of waste as it is transported.

Meteorology is a primary determinant of the opportunity to control atmospheric transport of contaminants. For example, manufacturing, transportation, and hazardous waste generating, processing, and storage facilities must be sited to avoid areas where specific local weather patterns are frequent and persistent. These avoidance areas include ground-based inversions, elevated inversions, valley winds, shore breezes, and city heat islands. In each of these venues, the pollutants become locked into air masses with little or no chance of moving out of the respective areas. Thus, the concentrations of pollutants can quickly and greatly pose risks to public health and the environment. In the soil environment the engineer has the opportunity to site facilities in areas of great depth to groundwater as well as in soils (e.g., clays) with very slow rates of transport. In this way, engineers and scientists must work closely with city and regional planners early in the site selection phases.[12] As the Bhopal incident has tragically illustrated, human factors must be considered along with physical factors. Planners, therefore, are an asset to any green site selection team.

Intervention to Control the Exposure

We now enter territory familiar to conventional engineering. We need to establish controls to prevent or at least reduce exposures to any pollutants that remain after prevention steps have been taken. In other words, we need to design systems to protect potential receptors.

The receptor of contamination can be a human being, other fauna in the general scheme of living organisms, flora, or materials or constructed facilities. In the case of humans, as we discussed earlier, the contaminant can be ingested, inhaled, or dermally contacted. Such exposure can be direct with human contact to, for example, particles of lead that are present in inhaled indoor air. Such exposure also can be indirect, as in the case of human ingestion of the cadmium and other heavy metals found in the livers of beef cattle that were raised on grasses receiving nutrition from cadmium-laced municipal wastewater treatment biosolids (commonly known as *sludge*).

Heavy metals or chlorinated hydrocarbons can be delivered similarly to domestic animals and animals in the wild. Construction materials also are sensitive to exposure to released substances, from the "greening" of statutes through the de-zincing process associated with low-pH rain events to the crumbling of stone bridges found in nature. Isolating potential receptors from exposure to hazardous chemicals, the engineer has an opportunity to control risks to those receptors.

The opportunities to control exposures to contaminants are associated directly with the ability to control the amount of hazardous pollutants delivered to the receptor through source control and siting of hazardous waste management facilities. One solution to environmental contamination could be to increase their dilution in water, air, or soil environments. We discuss specific examples of this type of intervention later in the chapter.

Intervention at the Point of Response

Most of the experience in addressing chemical contamination has been at the point where the threat already exists. Something is already contaminated, so we need to respond to the threat.

Opportunities for intervention at this point of response are grounded in basic scientific principles, engineering designs and processes, and applications of proven and developing technologies to control the risks associated with contaminants. Let us consider thermal processing as a class of hazardous control technology that is widely used in treating wastes but which has crucial pollution components.

THERMODYNAMICS AND STOICHIOMETRY

If completely organic in structure, contaminants are, in theory, completely destructible using principles based in thermodynamics with the engineering inputs and outputs summarized as

$$\text{hydrocarbons} + O_2(+\text{energy?}) \rightarrow CO_2 + H_2O(+\text{energy?}) \tag{3.1}$$

Contaminants are mixed with oxygen, sometimes in the presence of an external energy source, and in fractions of seconds or several seconds the by-products of gaseous carbon dioxide and water produced exit the top of the reaction vessel while a solid ash is produced and exits the bottom of the reaction vessel.[13] Energy may also be produced during the reaction and the heat may be recovered. Although CO_2 and H_2O production is a measure of success, a derivative problem in this simple reaction could be global warming associated with carbon dioxide.

Conversely, if the contaminant of concern to the engineer contains other chemical constituents, in particular chlorine and/or heavy metals, the original simple input and output relationship is modified to a very complex situation:

$$\begin{aligned}&\text{hydrocarbons} + O_2(+\text{energy?}) + \text{Cl or heavy metal(s)} + H_2O\\&+ \text{inorganic salts} + \text{nitrogen compounds}\\&+ \text{sulfur compounds} + \text{phosphorus compounds} \rightarrow CO_2 + H_2O\ (+\text{energy?})\\&+ \text{chlorinated hydrocarbons or heavy metal(s) inorganic salts}\\&+ \text{nitrogen compounds} + \text{sulfur compounds} + \text{phosphorus compounds}\end{aligned} \tag{3.2}$$

With these contaminants the potential exists for destruction of the initial contaminant, but actually exacerbating the problem by generating more hazardous off-gases containing chlorinated hydrocarbons and/or ashes containing heavy metals (e.g., the improper incineration of certain chlorinated hydrocarbons can lead to the formation of the highly toxic chlorinated dioxins, furans, and hexachlorobenzene). All of the thermal systems discussed below have common attributes. All require the balancing of the three "T's" of the science, engineering, and technology of incineration of any substance:

1. Time of incineration
2. Temperature of incineration
3. Turbulence in the combustion chamber

The advantages of thermal systems include (1) a potential for energy recovery; (2) volume reduction of the contaminant; (3) detoxification as selected molecules are reformulated; (4) basic scientific principles, engineering designs, and technologies that are well understood from a wide range of other applications, including electric generation and municipal solid waste incineration; (5) application to most organic contaminants, which comprise a large percentage of the total contaminants generated worldwide; (6) the possibility to scale the technologies to handle a single gallon per pound (liter per kilogram) of waste or millions of gallon per pound (liter per kilogram) of waste: and (7) land areas that are small compared to many other facilities (e.g., landfills). In all processes involving thermal destruction, the ultimate products will include CO_2, a known greenhouse gas. Thus, even a successful design will contribute to global problems, so the most preferable approach is to avoid the pollution in the first place.

Each system design must be customized to address the specific contaminants under consideration, including the quantity of waste to be processed over the planning period as well as the physical, chemical, and microbiological characteristics of the waste over the planning period of the project. The space required for the incinerator itself ranges from several square yards, to possibly the back of a flatbed truck, to several acres used to sustain a regional incinerator system. Laboratory testing and pilot studies matching a given waste to a given incinerator must be conducted prior to the design, siting, and construction of each incinerator. Generally, the same reaction applies to most thermal processes: gasification, pyrolysis, hydrolysis, and combustion[14]:

$$\begin{aligned} C_{20}H_{32}O_{10} + x_1O_2 + x_2H_2O \xrightarrow{\Delta} {} & y_1C + y_2CO_2 + y_3CO + y_4H_2 \\ & + y_5CH_4 + y_6H_2O + y_7C_nH_m \end{aligned} \tag{3.3}$$

The coefficients x and y balance the compounds on either side of the equation. The delta above the arrow indicates heating. In many thermal reactions, C_nH_m includes the alkanes, C_2H_2, C_2H_4, C_2H_6, C_3H_8, C_4H_{10}, and C_5H_{12}, and benzene, C_6H_6. Of all of the thermal processes, incineration is the most common process for destroying organic contaminants in industrial wastes. Incineration is simply the heating of wastes in the presence of oxygen to oxidize organic compounds (both toxic and nontoxic). The principal incineration steps are shown in Figure 3.6.

Applying Thermal Processes for Treatment

A word of warning when choosing incineration as the recommended technology: The mere mention of "incineration" evokes controversy in communities, as there

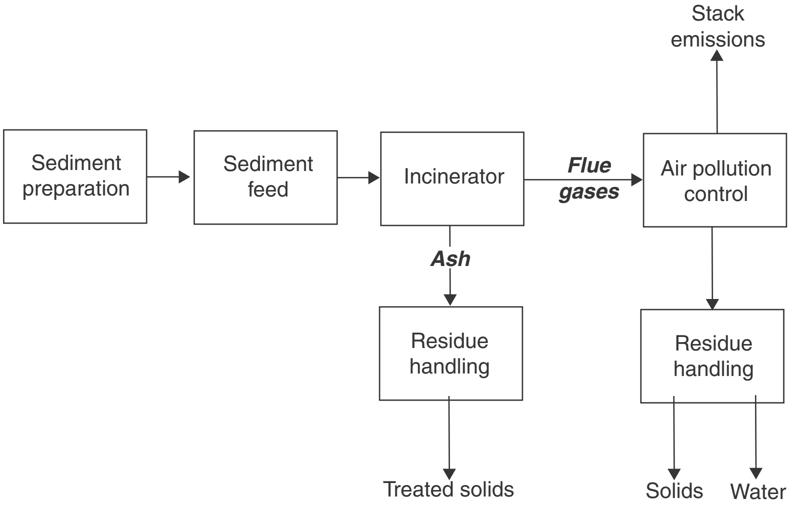


Figure 3.6 Steps in the incineration of contaminants.

From U.S. Environmental Protection Agency, Remediation Guidance Document, EPA-905-B94-003, Chapter 7, U.S. EPA, Washington, DC, 2003.

have been real and perceived failures. It is also important to note that incineration alone does not "destroy" heavy metals, it simply changes the valence of the metal. In fact, incineration can increase the leachability of metals via oxidation, although processes such as slagging (operating at sufficiently high temperatures to melt and remove incombustible materials) or vitrification (producing a nonleachable, basaltlike residue) actually reduce the mobility of many metals, making them less likely to come into contact with people and other receptors.

Leachability is a measure of the ease with which compounds in a waste can move into the accessible environment. The increased leachability of metals would be problematic if the ash and other residues are to be buried in landfills or stored in piles. From a green engineering standpoint, when reusing an old industrial side (i.e. a brown field), the leachability of metals at that side must be managed. The leachability of metals is generally measured by the toxicity characteristic leaching procedure (TCLP) test, discussed earlier in the chapter. Incinerator ash that fails the TCLP must be disposed of in a waste facility approved for hazardous wastes. Enhanced leachability is advantageous only if the residues are engineered to undergo an additional treatment step for metals. Again, the engineer must see incineration of but one component within a systematic approach within the life cycle.

There are a number of places in the incineration flow of the contaminant through the incineration process where new compounds may need to be addressed. As mentioned, ash and other residues may contain high levels of metals, at least higher than the original feed. The flue gases are likely to include both organic and inorganic compounds that have been released as a result of temperature-induced volatilization and/or newly transformed products of incomplete combustion with higher vapor pressures than those of the original contaminants.

The disadvantages of hazardous waste incinerators include the following: (1) the equipment is capital-intensive, particularly the refractory material lining the inside walls of each combustion chamber, which must be replaced as cracks form due to the contraction and expansion whenever a combustion system is cooled and heated; (2) operation of the equipment requires very skilled operators and is more costly when fuel must be added to the system; (3) ultimate disposal of the ash is necessary and particularly troublesome and costly if heavy metals and/or chlorinated compounds are found during the expensive monitoring activities; and (4) air emissions may be hazardous and thus must be monitored for chemical constituents and controlled.

Given these underlying principles of incineration, seven general guidelines emerge:

1. Only purely organic liquid contaminants are true candidates for combustion.
2. Chlorine-containing organic materials deserve special consideration if in fact they are to be incinerated at all; special materials used in the construction of the incinerator, long (many seconds) of combustion time, high temperatures (>1600°C), with continuous mixing if the contaminant is in solid or sludge form.
3. Feedstock containing heavy metals generally should not be incinerated.
4. Sulfur-containing organic material will emit sulfur oxides, which must be controlled.
5. The formation of nitrogen oxides can be minimized if the combustion chamber is maintained above 1100°C.
6. Destruction depends on the interaction of a combustion chamber's temperature, dwell time, and turbulence.
7. Off-gases and ash must be monitored for chemical constituents; each residual must be treated as appropriate so that the entire combustion system operates within the requirements of local, state, and federal environmental regulators, and hazardous components of the off-gases, off-gas treatment processes, and the ash must reach ultimate disposal in a permitted facility.

Thus, the decision of whether to incinerate waste must be a green one. That is, the designer should consider ways to eliminate the generation of any wastes at the outset, and decide the most sustainable methods for any remaining wastes.

Thermal Destruction Systems

The green engineer must carefully match the control technologies in a project to the problems at hand. If these technologies are to treat hazardous wastes thermals, this decision can be the difference between success and failure of the life cycle.

The types of thermal systems vary considerably. Five general categories are available to destroy contaminants: (1) rotary kiln, (2) multiple hearth, (3) liquid injection, (4) fluidized bed, and (5) multiple chamber.

Rotary Kiln

The combustion chamber in a rotary kiln incinerator such as the one illustrated in Figure 3.7 is a heated rotating cylinder that is mounted at an angle with possible baffles added to the inner face to provide the turbulence necessary for the target three T's for the contaminant destruction process to take place. Engineering design decisions, based on the results of laboratory testing of a specific contaminant, include (1) angle of the drum, (2) diameter and length of the drum, (3) presence and location of the baffles, (4) rotational speed of the drum, and (5) use of added fuel to increase the temperature of the combustion chamber as the specific contaminant requires. The liquid, sludge, or solid hazardous waste is input into the upper end of the rotating cylinder, rotates with the

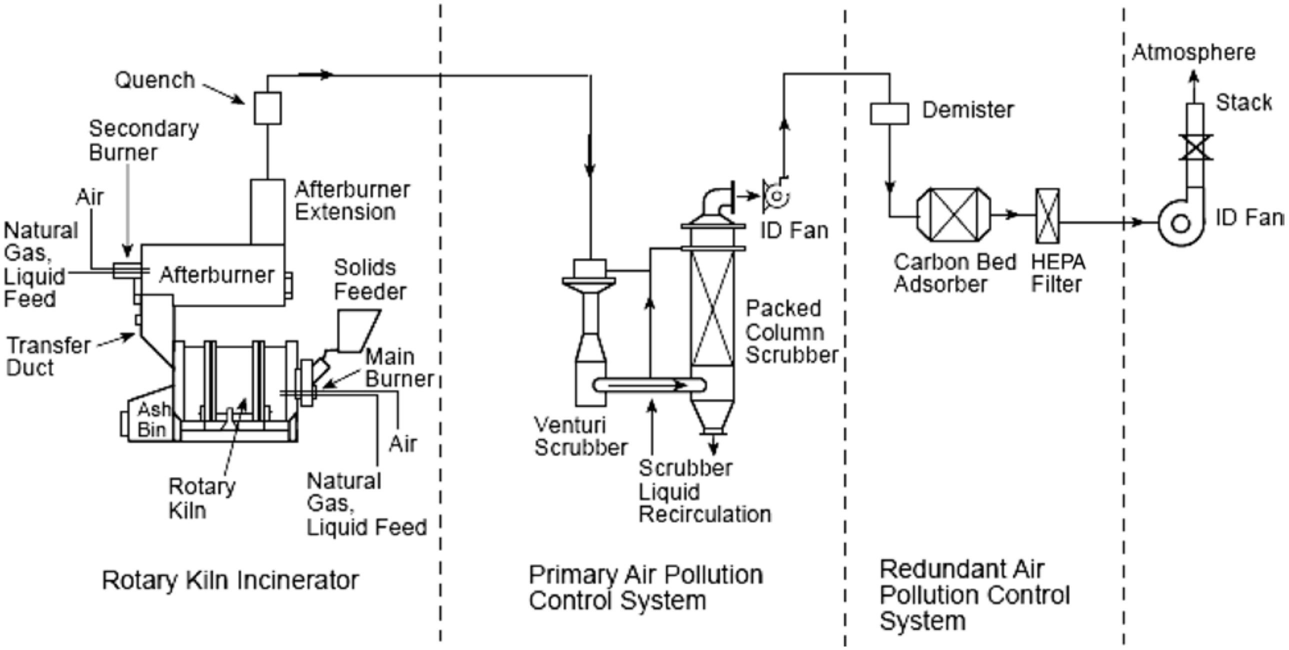


Figure 3.7 Rotary kiln system.

Adapted from J. Lee, D. Fournier, Jr., C. King, S. Venkatesh, and C. Goldman, *Project Summary: Evaluation of Rotary Kiln Incinerator Operation at Low-to-Moderate Temperature Conditions*, U.S. EPA, Washington, DC, 1997.

cylinder-baffle system, and falls with gravity to the lower end of the cylinder. The heated upward-moving off-gases are collected, monitored for chemical constituents, and subsequently treated as appropriate prior to release, while the ash falls with gravity to be collected, monitored for chemical constituents, and treated as needed before ultimate disposal. The newer rotary kiln systems[15] consist of a primary combustion chamber, a transition volume, and a fired afterburner chamber. After exiting the afterburner, the flue gas is passed through a quench section followed by a primary APCS. The primary air pollution control system (APCS) can be a venture scrubber followed by a packed-column scrubber. Downstream of the primary APCS, a backup secondary APCS, with a demister, an activated-carbon adsorber, and a high-efficiency particulate air (HEPA) filter can collect contaminants not destroyed by the incineration.

The rotary kiln is applicable to the incineration of most organic contaminants, it is well suited for solids and sludges, and in special cases, liquids and gases can be injected through auxiliary nozzles in the side of the combustion chamber. Operating temperatures generally vary from 800 to 1650°C. Engineers use laboratory experiments to design residence times of seconds for gases and minutes or possibly hours for the incineration of solid material.

Multiple-Hearth System

In the multiple-hearth system illustrated in Figure 3.8 contaminants in solid or sludge form are generally fed slowly through the top vertically stacked hearth; in special configurations hazardous gases and liquids can be injected through side nozzles. Multiple-hearth incinerators, historically developed to burn municipal wastewater treatment biosolids, rely on gravity and scrapers working the upper edges of each hearth to transport the waste through holes from upper hotter hearths to lower cooler hearths. Heated upward-moving off-gases are collected, monitored for chemical constituents, and treated as appropriate prior to release; the falling ash is collected, monitored for chemical constituents, and treated prior to ultimate disposal.

Most organic wastes generally can be incinerated using a multiple-hearth configuration. Operating temperatures generally vary from 300 to 980°C. These systems are designed with residence times of seconds if gases are fed into the chambers, to several hours if solid materials are placed on the top hearth and eventually allowed to drop to the bottom hearth, exiting as ash.

Liquid Injection

Vertical or horizontal nozzles spray liquid hazardous wastes into liquid injection incinerators designed especially for the task or as a retrofit to one of the other incinerators discussed here. The wastes are atomized through the nozzles that

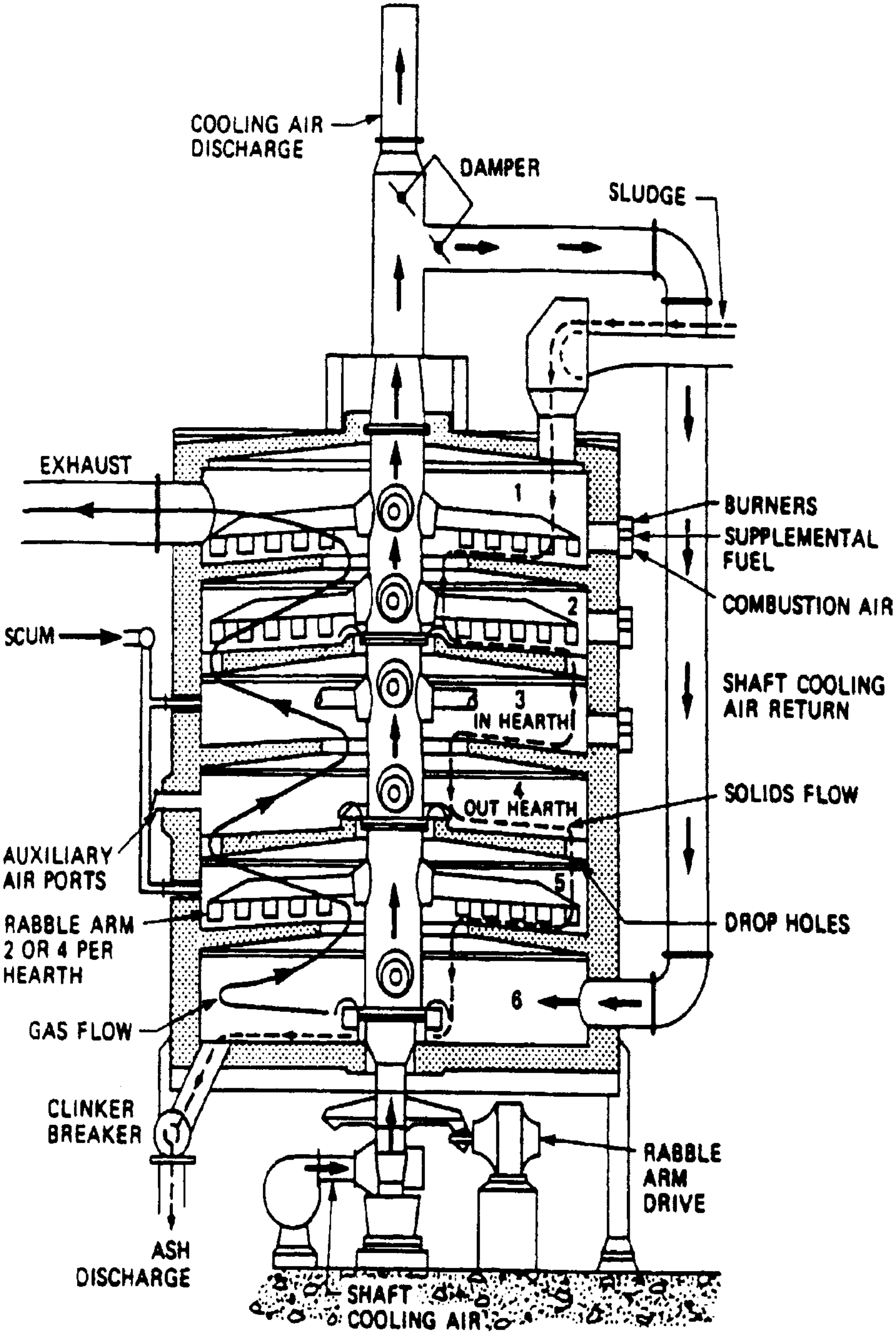


Figure 3.8 Multiple-hearth incineration system.

From U.S. Environmental Protection Agency, "Locating and estimating air emissions from sources of benzene," EPA/454/R-98/011, U.S. EPA, Research Triangle Park, NC, 1998.

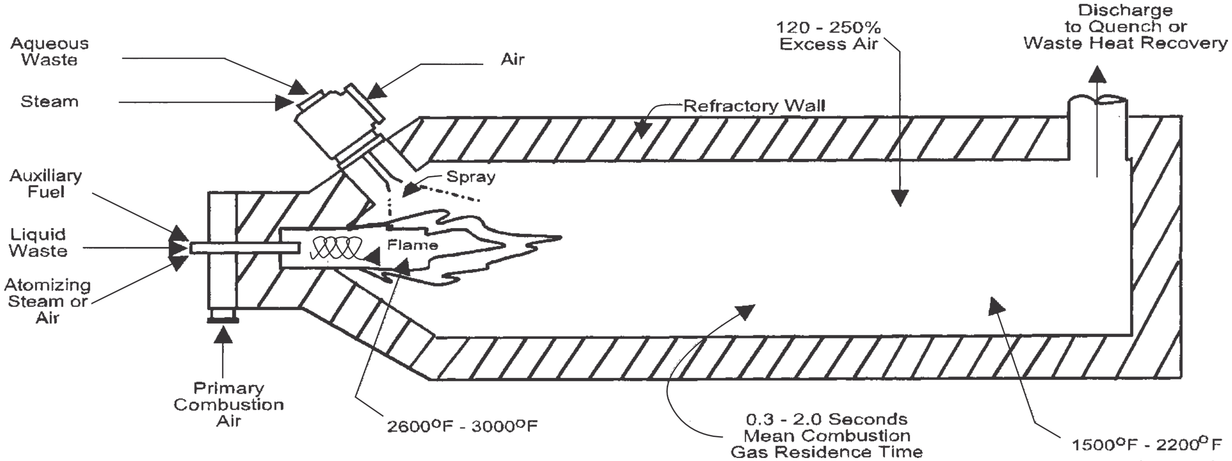


Figure 3.9 Prototype of a liquid injection system.

From U.S. Environmental Protection Agency, "Locating and estimating air emissions from sources of benzene," EPA/454/R-98/011, U.S. EPA, Research Triangle Park, NC, 1998.

match the waste being handled with the combustion chamber as determined in laboratory testing. The application is obviously limited to liquids that do not clog these nozzles, although some success has been experienced with hazardous waste slurries. Operating temperatures generally vary from 650 to 1650°C (1200 to 3000°F). Liquid injection systems (Fig. 3.9) are designed with residence times of fractions of seconds as off-gases. The upward-moving off-gases are collected, monitored for chemical constituents, and treated as appropriate prior to release to the lower troposphere.

Fluidized Bed

Contaminated feedstock is injected under pressure into a heated bed of agitated inert granular particles, usually sand, as the heat is transferred from the particles to the waste, and the combustion process proceeds as summarized in Figure 3.10. External heat is applied to the particle bed prior to the injection of the waste and is applied continually throughout the combustion operation as the situation dictates. Heated air is forced into the bottom of the particle bed and the particles become suspended among themselves during this continuous fluidizing process. The openings created within the bed permit the introduction and transport of the waste into and through the bed. The process enables the contaminant to come into contact with particles that maintain their heat better than, for example, the gases inside a rotary kiln. The heat maintained in the particles increases the time the contaminant is in contact with a heated element, and thus the combustion process could become more complete with fewer harmful by-products. Off-gases are collected, monitored for chemical constituents, and

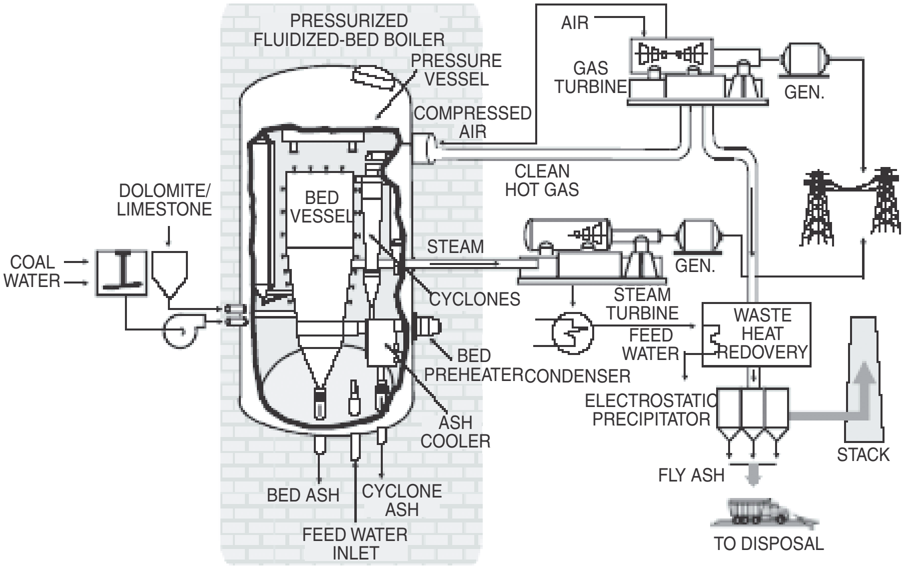


Figure 3.10 Pressurized fluidized-bed system.

From U.S. Department of Energy, TIDD PFBC Demonstration Project, U.S. DoE, Washington, DC, 1999.

treated as appropriate prior to release, and the falling ash is collected, monitored for chemical constituents, and subsequently treated prior to ultimate disposal.

Most organic wastes can be incinerated in a fluidized bed, but the system is best suited for liquids. Operating temperatures generally vary from 750 to 900°C. Liquid injection systems are designed with residence times of fractions of seconds as off-gases. The upward-moving off-gases are collected, monitored for chemical constituents, and treated as appropriate prior to release to the lower troposphere.

Multiple-Chamber System

Contaminants are turned into a gaseous form on a grate in the ignition chamber of a multiple-chamber system. The gases created in this ignition chamber travel through baffles to a secondary chamber where the actual combustion process takes place. Often, the secondary chamber is located above the ignition chamber to promote natural advection of the hot gases through the system. Heat may be added to the system in either the ignition chamber or the secondary chamber, as required for specific burns.

The application of multiple-chamber incinerators generally is limited to solid wastes, with the waste entering the ignition chamber through an open charging door in batch, not continuous, loading. Combustion temperatures typically hover near 540°C for must applications. These systems are designed with residence times of minutes to hours for solid hazardous wastes as off-gases are collected, monitored for chemical constituents, and treated as appropriate prior to release to the lower troposphere. At the end of each burn period the system must be cooled so that the ash can be removed prior to monitoring for chemical constituents and subsequent treatment prior to ultimate disposal.

CALCULATING DESTRUCTION REMOVAL

Federal hazardous waste incineration standards require that hazardous organic compounds meet certain destruction efficiencies. These standards require that any hazardous waste undergo 99.99% destruction of all hazardous wastes and 99.9999% destruction of extremely hazardous wastes such as dioxins. The destruction removal efficiency (DRE) is calculated as

$$\mathrm{DRE} = \frac{W_{\mathrm{in}} - W_{\mathrm{out}}}{W_{\mathrm{in}}} \times 100 \tag{3.4}$$

where W_{in} is the rate of mass of waste flowing into the incinerator and W_{out} is the rate of mass of waste flowing out of the incinerator. For example, let us calculate the DRE if during a stack test, the mass of pentachlorodioxin is loaded into incinerator at the rate of 10 mg min^{-1}, and the mass flow rate of the compound measured downstream in the stack is 200 picograms (pg) min^{-1}. Is the incinerator up to code for the thermal destruction of this dioxin?

$$\mathrm{DRE} = \frac{W_{\mathrm{in}} - W_{\mathrm{out}}}{W_{\mathrm{in}}} \times 100 = \frac{10\ \mathrm{mg\ min^{-1}} - 200\ \mathrm{pg\ min^{-1}}}{10\ \mathrm{mg\ min^{-1}}} \times 100$$

Since 1 pg $= 10^{-12}$ g and 1 mg $= 10^{-3}$, then 1 pg $= 10^{-9}$ mg. So

$$\frac{10\,\mathrm{mg\,min^{-1}} - 200 \times 10^{-9}\,\mathrm{mg\,min^{-1}}}{10\,\mathrm{mg\,min^{-1}}} \times 100 = 999999.98\%\ \text{removal}$$

Even if pentachlorodioxin is considered to be "extremely hazardous," this is better than the "rule of six nines" so the incinerator is operating up to code.

If we were to calculate the DRE value during the same stack test for the mass of tetrachloromethane (CCl_4) loaded into incinerator at the rate of 100 L min^{-1} and the mass flow rate of the compound measured downstream is 1 mL min^{-1}. Is the incinerator up to code for CCl_4? This is a lower removal rate since 100 L is in and 0.001 is leaving, so the DRE = 99.999. This is acceptable (i.e., better removal efficiency than 99.99% by an order of magnitude), as long as CCl_4 is not considered an extremely hazardous compound. If it were, it would have to meet the rule of six nines (it has only five).

By the way, both of these compounds are chlorinated. As mentioned, special precautions must be taken when dealing with such halogenated compounds, since even more toxic compounds than those being treated can end up being generated. Incomplete reactions are very important sources of environmental contaminants. For example, these reactions generate products of incomplete combustion, such as dioxins, furans, carbon monoxide, polycyclic aromatic hydrocarbons, and hexachlorobenzene. Thus, whether a system is classified as green, at least in the case of treatment, is quantifiable.

Formation of Unintended By-products

One of the major incentives for pollution prevention is that with some amount of forethought we should be able to avoid the creation of toxic by-products. If we choose a production cycle that greatly reduces the creation of toxic substances or that generates a different, less toxic by-product, we have avoided undue costs, legal problems, and risks down the road. This can be demonstrated by the troublesome and downright scary pollutant, dioxin.

Chlorinated dioxins have 75 different forms and there are 135 different chlorinated furans, simply by the number and arrangement of chlorine atoms on the molecules. The compounds can be separated into groups that have the same number of chlorine atoms attached to the furan or dioxin ring. Each form varies in its chemical, physical, and toxicological characteristics (see Fig. 3.11).

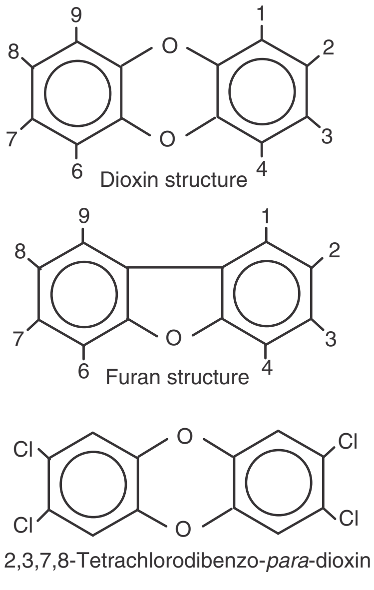


Figure 3.11 Molecular structures of dioxins and furans. Bottom structure is of the most toxic dioxin congener, tetrachlorodibenzo-*para*-dioxin, formed by the substitution of chlorine for hydrogen atoms at positions 2, 3, 7, and 8 on the molecule.

Dioxins are highly toxic compounds that are created unintentionally during combustion processes. The most toxic form is the 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (TCDD) isomer. Other isomers with the "tetra" configuration are also considered to have higher toxicity than the dioxins and furans with different chlorine atom arrangements.

Knowing how these compounds are formed is the first step in reducing or eliminating them. The chemical and physical mechanisms that lead to the production of dioxin involve the halogen chlorine. Incinerators of chlorinated wastes are the most common environmental sources of dioxins, accounting for about 95% of the volume produced in the United States.

The emission of dioxins and furans from combustion processes may follow three general physicochemical pathways. The first pathway occurs when the feed material going to the incinerator contains dioxins and/or furans and a fraction of these compounds survives thermal breakdown mechanisms and pass through to be emitted from vents or stacks. This is not considered to account for a large volume of dioxin released to the environment, but it may account for the production of dioxinlike, coplanar PCBs.

The second process is the formation of dioxins and furan from the thermal breakdown and molecular rearrangement of precursor compounds, such as the chlorinated benzenes, chlorinated phenols (such as pentachlorophenol), and PCBs, which are chlorinated aromatic compounds with structural resemblances to the chlorinated dioxin and furan molecules. Dioxins appear to form after the precursor has condensed and adsorbed onto the surface of particles, such as fly ash. This is a heterogeneous process,* where the active sorption sites on the particles allow for the chemical reactions, which are catalyzed by the presence of inorganic chloride compounds and ions sorbed to the particle surface. The process occurs within the temperature range 250 to 450°C, so most of the dioxin formation under the precursor mechanism occurs away from the high-temperature zone in the incinerator, where the gases and smoke derived from combustion of the organic materials have cooled during conduction through flue ducts, heat exchanger and boiler tubes, air pollution control equipment, or the vents and the stack.

The third means of synthesizing dioxins is de novo within the "cool zone" of the incinerator, wherein dioxins are formed from moieties different from those of the molecular structure of dioxins, furans, or precursor compounds. Generally, these can include a wide range of both halogenated compounds such as polyvinyl chloride, and nonhalogenated organic compounds such as petroleum products, nonchlorinated plastics (polystyrene), cellulose, lignin, coke, coal, and inorganic compounds such as particulate carbon and hydrogen chloride gas. No matter which de novo compounds are involved, however, the process needs a chlorine donor (a molecule that "donates" a chlorine atom to the precursor molecule).

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*A heterogeneous reaction occurs in more than one physical phase (solid, liquid or gas).

Table 3.6 Concentrations (mg g^{-1}) of Chlorinated Dioxins and Furans after Heating Mg–Al Silicate, 4% Charcoal, 7% Cl, 1% $CuCl_2 \bullet H_2O$ at 300°C

	Reaction Time (hours)				
Compound	0.25	0.5	1	2	4
Tetrachlorodioxin	2	4	14	30	100
Pentachlorodioxin	110	120	250	490	820
Hexachlorodioxin	730	780	1,600	2,200	3,800
Heptachlorodioxin	1,700	1,840	3,500	4,100	6,300
Octachlorodioxin	800	1,000	2,000	2,250	6,000
Total chlorinated Dioxins	3,342	3,744	7,364	9,070	17,020
Tetrachlorofuran	240	280	670	1,170	1,960
Pentachlorofuran	1,360	1,670	3,720	5,550	8,300
Hexachlorofuran	2,500	3,350	6,240	8,900	14,000
Heptachlorofuran	3,000	3,600	5,500	6,700	9,800
Octachlorofuran	1,260	1,450	1,840	1,840	4,330
Total chlorinated furans	8,360	10,350	17,970	24,160	38,390

Source: L. Stieglitz, G. Zwick, J. Beck, H. Bautz, and W. Roth, *Chemosphere*, 19, 283, 1989.

This leads to the formation and chlorination of a chemical intermediate that is a precursor. The reaction steps after this precursor is formed can be identical to the precursor mechanism discussed in the preceding paragraph.

De novo formation of dioxins and furans may involve even more fundamental substances than those moieties mentioned above. For example, dioxins may be generated[16] by heating of carbon particles absorbed with mixtures of magnesium–aluminum silicate complexes when the catalyst copper chloride ($CuCl_2$) is present (see Table 3.6 and Fig. 3.12). The de novo formation of chlorinated dioxins and furans from the oxidation of carbonaceous particles seems to occur at around 300°C. Other chlorinated benzenes, chlorinated biphenyls, and chlorinated naphthalene compounds are also generated by this type of mechanism.

Thus, green engineering must account for the potential that dioxin's may be generated during any of these processes. Good operations and maintenance will translate into the lower rates of production of hazardous substances, or ideally no hazardous waste production at all.

Other processes generate dioxin pollution. A source that has been greatly reduced in the last decade is the paper production process, which formerly used chlorine bleaching. This process has been changed dramatically, and most paper mills no longer use chlorine. Dioxin is also produced in the making of PVC plastics, which may follow chemical and physical mechanisms similar to the second and third processes discussed above.

Since dioxin and dioxinlike compounds are lipophilic and persistent, they accumulate in soils, sediments, and organic matter and can persist in solid and hazardous waste disposal sites.[17] These compounds are semivolatile, so they may

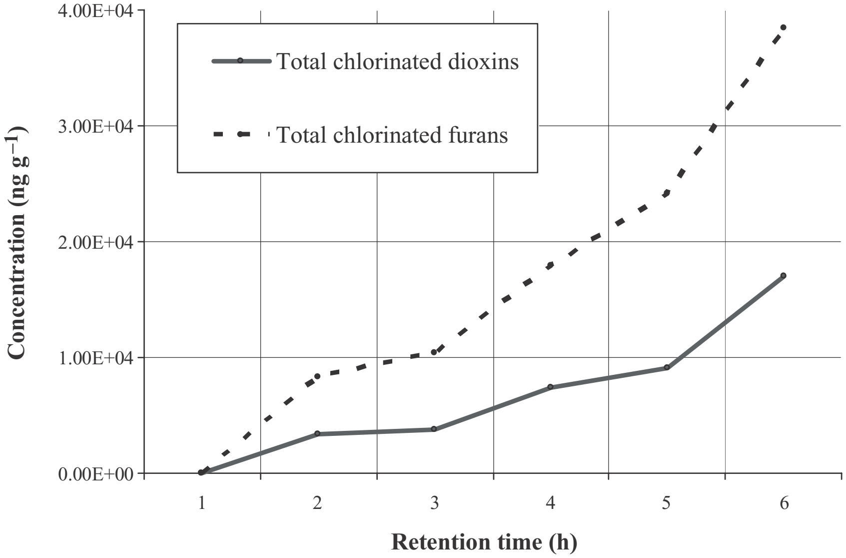


Figure 3.12 De novo formation of chlorinated dioxins and furans after heating Mg–Al silicate, 4% charcoal, 7% Cl, 1% $CuCl_2 \cdot H_2O$ at 300°C.

Adapted from L. Stieglitz, G. Zwick, J. Beck, H. Bautz, and W. Roth, *Chemosphere* 19, 283, 1989.

migrate away from these sites and be transported in the atmosphere either as aerosols (solid and liquid phase) or as gases (the portion of the compound that volatilizes). Therefore, the engineer must take great care in removal and remediation efforts so as not to unwittingly cause releases from soil and sediments via volatilization or via perturbations such as landfill and dredging operations.

Processes Other Than Incineration

Incineration is frequently used to decontaminate substrates with elevated concentrations of organic hazardous constituents. High-temperature incineration may not, however, be needed to treat soils contaminated with most volatile organic compounds. Also, in soils with heavy metals, high-temperature incineration will probably increase the volatilization of some of these metals into the combustion flue gas (see Tables 3.7 and 3.8). High concentrations of volatile trace metal compounds in the flue gas pose increased challenges to air pollution control. Thus, other thermal processes (i.e., thermal desorption and pyrolysis) can provide an effective alternative to incineration.

When successful in decontaminating substrates, especially soils, to the necessary treatment levels, thermally desorbing contaminants has the additional benefit of lower fuel consumption, no formation of slag, less volatilization of metal compounds, and less complicated air pollution control demands than other methods. So beyond monetary costs and ease of operation, a less energy (heat)-intensive system can be more advantageous in terms of actual pollutant removal efficiency.

Table 3.7 Conservative Estimates of Heavy Metals and Metalloids Partitioning to Flue Gas as a Function of Solids Temperature and Chlorine Content (Percent)[a]

	871°C		1093°C	
Metal or Metalloid	Cl = 0%	Cl = 1%	Cl = 0%	Cl = 1%
Antimony	100	100	100	100
Arsenic	100	100	100	100
Barium	50	30	100	100
Beryllium	5	5	5	5
Cadmium	100	100	100	100
Chromium	5	5	5	5
Lead	100	100	100	100
Mercury	100	100	100	100
Silver	8	100	100	100
Thallium	100	100	100	100

Source: U.S. Environmental Protection Agency, *Guidance on Setting Permit Conditions and Reporting Trial Burn Results*, Vol. II, *Hazardous Waste Incineration Guidance Series*, EPA/625/6-89/019. U.S., EPA, EPA, Washington, DC; 1989.

[a] The remaining percentage of metal is contained in the bottom ash. Partitioning for liquids is estimated at 100% for all metals. The combustion gas temperature is expected to be 100 to 1000°F higher than the solids temperature.

Table 3.8 Metal and Metalloid Volatilization Temperatures

	Without Chlorine		With 10% Chlorine	
Metal or Metalloid	Volatility Temperature (°C)	Principal Species	Volatility Temperature (°C)	Principal Species
Chromium	1613	CrO_2/CrO_3	1611	CrO_2/CrO_3
Nickel	1210	$Ni\ (OH)_2$	693	$NiCl_2$
Beryllium	1054	$Be\ (OH)_2$	1054	$Be\ (OH)_2$
Silver	904	Ag	627	AgCl
Barium	841	$Ba\ (OH)_2$	904	$BaCl_2$
Thallium	721	Tl_2O_3	138	TIOH
Antimony	660	Sb_2O_3	660	Sb_2O_3
Lead	627	Pb	−15	$PbCl_4$
Selenium	318	SeO_2	318	SeO_2
Cadmium	214	Cd	214	Cd
Arsenic	32	As_2O_3	32	As_2O_3
Mercury	14	Hg	14	Hg

Source: B. Willis, M. Howie, and R. Williams, *Public Health Reviews of Hazardous Waste Thermal Treatment Technologies: A Guidance Manual for Public Health Assessors*. Agency for Toxic Substances and Disease Registry, Washington, DC, 2002.

Pyrolysis

Pyrolysis is the process of chemical decomposition induced in organic materials by heat in the absence of oxygen. It is practicably impossible to achieve a completely oxygen-free atmosphere, so pyrolytic systems run with less than stoichiometric quantities of oxygen. Because some oxygen will be present in any pyrolytic system, there will always be a small amount of oxidation. Also, desorption will occur when volatile or semivolatile compounds are present in the feed.

During pyrolysis[18] organic compounds are converted to gaseous components, along with some liquids, as coke (i.e., the solid residue of fixed carbon and ash). CO, H_2, CH_4, and other hydrocarbons are produced. If these gases cool and condense, liquids will form and leave oily tar residues and water with high concentrations of total organic carbon. Pyrolysis generally takes place well above atmospheric pressure at temperatures exceeding 430°C. The secondary gases need their own treatment, such as by a secondary combustion chamber, by flaring, and by partial condensation. Particulates must be removed by additional air pollution controls (e.g., fabric filters or wet scrubbers).

Conventional thermal treatment methods, such as a rotary kiln, a rotary hearth furnace, or a fluidized-bed furnace, are used for waste pyrolysis. Kilns or furnaces used for pyrolysis may be of the same design as those used for combustion (i.e., incineration) discussed earlier, but operate at lower temperatures and with less air than in combustion.

The target contaminant groups for pyrolysis include semivolatile organic compounds, including pesticides, PCBs, dioxins, and polynuclear aromatic hydrocarbons (PAHs). It allows for separating organic contaminants from various wastes, including those from refineries, coal tar, wood preservatives, creosote and hydrocarbon-contaminated soils, mixed radioactive and hazardous wastes, synthetic rubber processing, and paint and coating processes. Pyrolysis systems may be used to treat a variety of organic contaminants that chemically decompose when heated (i.e., "cracking"). Pyrolysis is not effective in either destroying or physically separating inorganic compounds that coexist with the organics in the contaminated medium. Volatile metals may be removed and transformed, but of course the mass balance will not be changed.

Emerging Thermal Technologies

Other promising thermal processes include high-pressure oxidation and vitrification.[19] High-pressure oxidation combines two related technologies, wet air oxidation and supercritical water oxidation, which combine high temperature and pressure to destroy organics. Wet air oxidation can operate at pressures of about 10% of those used during supercritical water oxidation, an emerging technology that has shown some promise in the treatment of PCBs and other stable compounds that resist chemical reaction. Wet air oxidation has generally been limited to conditioning of municipal wastewater sludges but can degrade hydrocarbons (including PAHs), certain pesticides, phenolic compounds, cyanides, and other organic compounds. Oxidation may benefit from catalysts.

Vitrification uses electricity to heat and destroy organic compounds and immobilize inert contaminants. A vitrification unit has a reaction chamber divided into two sections: the upper section to introduce the feed material, containing gases and pyrolysis products, and the lower section consisting of a two-layer molten zone for the metal and siliceous components of the waste. Electrodes are inserted into the waste solids, and graphite is applied to the surface to enhance its electrical conductivity. A large current is applied, resulting in rapid heating of the solids and causing the siliceous components of the material to melt as temperatures reach about 1600°C. The end product is a solid, glasslike material that is very resistant to leaching.

All of these methods are energy intensive. This is another reason to avoid generating wastes in the first place.

Indirect Pollution

In addition to direct treatment, air pollution is a concern for other means of treating hazardous wastes, especially when these wastes are stored or treated more passively, such as in a landfill or aeration pond. Leachate collection systems (see Fig. 3.13) provide a way to collect wastes which can then be treated. However, such *pump-and-treat systems* can produce air pollutants. Actually, this often intentional. For example, groundwater is treated by drilling recovery wells to pump contaminated groundwater to the surface. Commonly used groundwater treatment approaches include air stripping, filtering with granulated activated carbon (GAC), and air sparging. Air stripping transfers volatile compounds from water to air (see Fig. 3.14). Ground water is allowed to drip downward in a tower filled with a permeable material through which a stream of air flows upward. Another method bubbles pressurized air through contaminated water in a tank. The air leaving the tank (i.e., the off-gas) is treated by removing gaseous pollutants. Filtering groundwater with GAC entails pumping the water through the GAC to trap the contaminants. In air sparging, air is pumped into groundwater to aerate the water. Most often, a soil venting system is combined with an air sparging system for vapor extraction, with the gaseous pollutants treated as in air stripping.

Regulatory agencies often require two or three pairs of these systems as design redundancies to protect the integrity of a hazardous waste storage or treatment facility. A primary leachate collection and treatment system must be designed like the bottom of a landfill bathtub. This leachate collection system must be graded

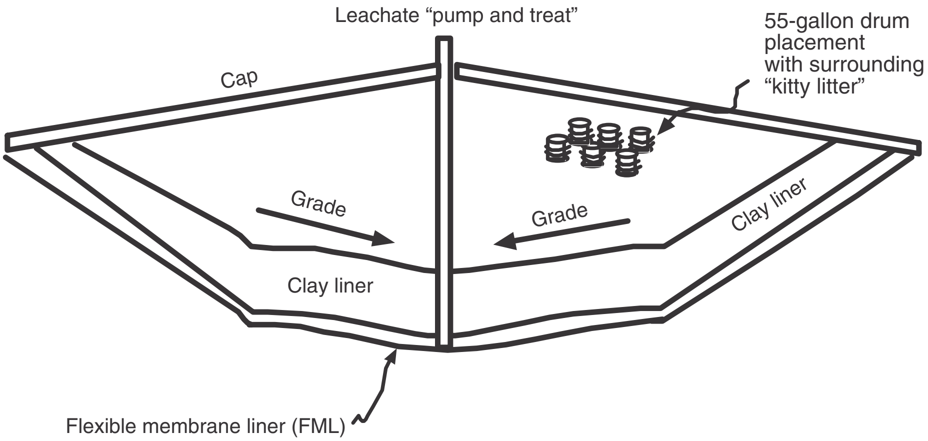


Figure 3.13 Leachate collection system for a hazardous waste landfill.

From D. Vallero, *Engineering the Risks of Hazardous Wastes*, Butterworth-Heinemann, Woburn, MA.

to promote the flow of liquid within the landfill from all points in the landfill to a central collection point where the liquid can be pumped to the surface for subsequent monitoring and treatment. Crushed stone and perforated pipes are used to channel the liquid along the top layer of this compacted clay liner to the pumping locations.

Thus, directly treating hazardous wastes physically and chemically, as with thermal systems, and controlling air pollutants indirectly, as when gases are released

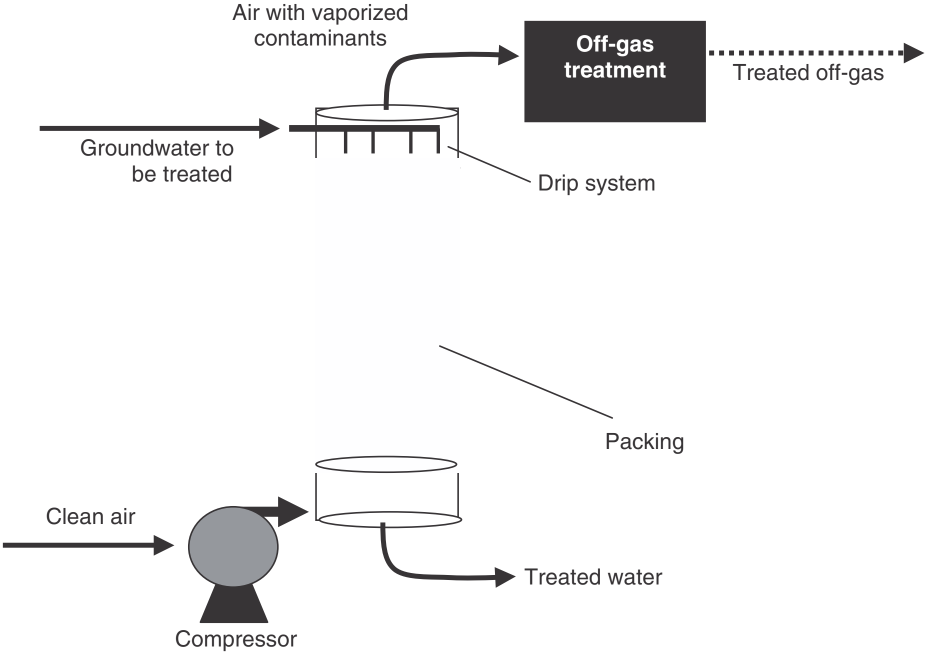


Figure 3.14 Air stripping system to treat volatile compounds in water.

from pump-and-treat systems, requires a comprehensive approach. Otherwise, we are merely moving the pollutants to different locations or even making matters worse by either rendering some contaminants more toxic or exposing receptors to dangerous substances.

BIOLOGY IS THE GREEN ENGINEER'S FRIEND

With the foregoing attention to physics and chemistry in green design, we must keep in mind that biology is invaluable in both active and passive treatment systems. This is well known in water and soil cleanup. However, it applies to all green technologies. For example, in recent decades air pollutants have been treated microbially. Waste streams containing volatile organic compounds (VOCs) may be treated with biological systems. These are similar to biological systems used to treat wastewater, classified as three basic types: (1) biofilters; (2) biotrickling filters; and (3) bioscrubbers.

Biofilms of microorganisms (bacteria and fungi) are grown on a porous medium in biofilters and biotrickling systems. The air or other gas containing the VOCs is passed through a biologically active medium, where the microbes break down the compounds to simpler compounds, eventually to carbon dioxide (if aerobic), methane (if anaerobic), and water. The major difference between biofiltration and trickling systems is how the liquid interfaces with the microbes. The liquid phase is stationary in a biofilter (see Fig. 3.15), but liquids move through the porous medium of a biotrickling system (i.e., the liquid "trickles").

A particularly green method of biofiltration uses compost as the porous medium. Compost contains numerous species of beneficial microbes that are already acclimated to organic wastes. Industrial compost biofilters have achieved removal rates at the 99% level. Biofilters are also the most common method for removing VOCs and odorous compounds from airstreams. In addition to a wide array of volatile chain and aromatic organic compounds, biological systems have successfully removed vapor-phase inorganics, such as ammonia, hydrogen sulfide, and other sulfides, including carbon disulfide and mercaptans. The operational key is the biofilm. The gas must interface with the film. In fact, this interface may also occur without a liquid phase (see Fig. 3.16). According to Henry's law, the compounds partition from the gas phase (in the carrier gas or airstream) to the liquid phase (biofilm). Compost has been a particularly useful medium in providing this partitioning.

The bioscrubber is a two-unit setup. The first unit is an adsorption unit. This unit may be a spray tower, bubbling scrubber, or packed column. After this unit, the airstream enters a bioreactor with a design quite similar to that of an activated sludge system in a wastewater treatment facility. Bioscrubbers are much less common than biofiltration systems in the United States.[20]

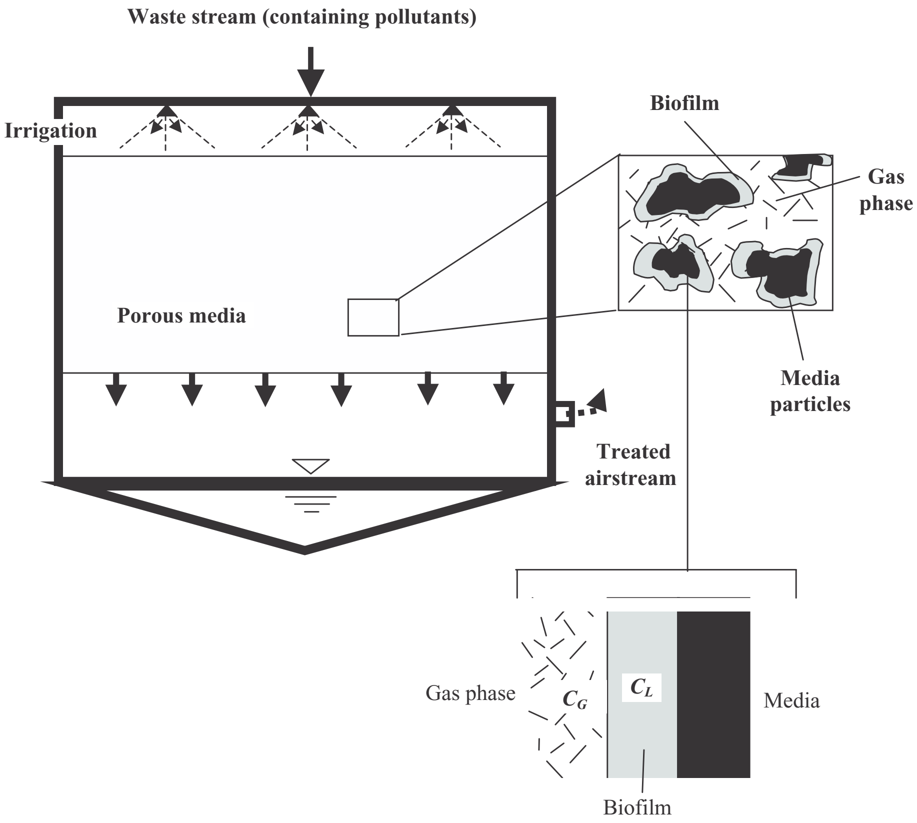


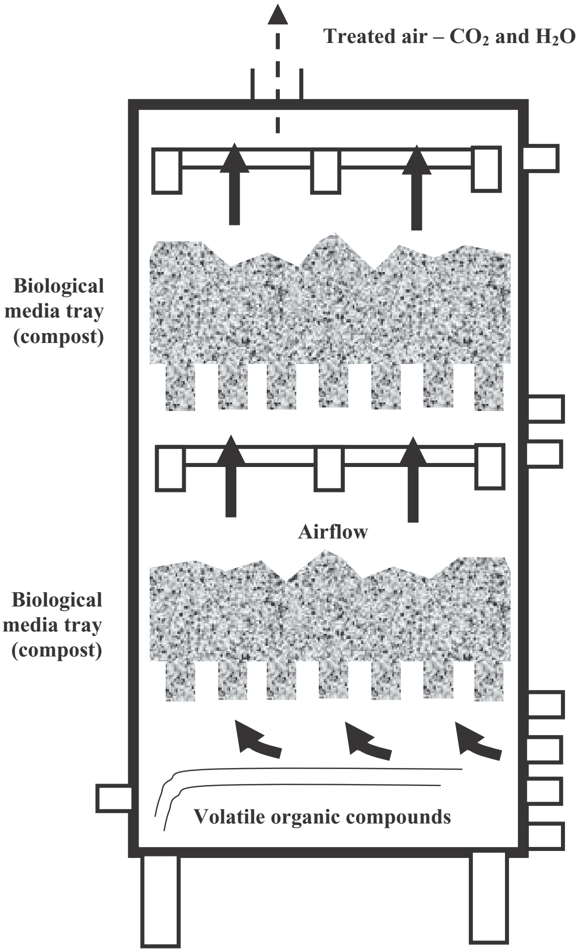
Figure 3.15 Packed bed biological control system to treat volatile compounds. Air containing gas-phase pollutants (C_G) traverses porous media. The soluble fraction of the volatilized compounds in the airstream partition into the biofilm (C_L) according to Henry's law: $C_L = C_G/H$, where *H* is the Henry's law constant.

From D.A. Vallero, *Fundamentals of Air Pollution*, 4th ed., Academic Press, San Diego, CA, 2007; adapted from S. J. Ergas and K. A. Kinney. Air and Waste Management Association, "Biological control systems," in *Air Pollution Control Manual*, 2nd ed., W. T. Davis, Ed., Wiley, New York, 2000, pp. 55–65.

All three types of biological systems have relatively low operating costs since they are operated near ambient temperature and pressure conditions. Power needs are generally for air movement, and pressure drops are low (<10 cm H_2O per meter of packed bed). Other costs include amendments (e.g., nutrients) and humidification. Another advantage is the usually small amount of toxic by-products, as well as low rates of emission of greenhouse gases (oxides of nitrogen and carbon dioxide) compared to thermal systems.

Success is highly dependent on the degradability of the compounds present in the airstream, their fugacity and the solubility needed to enter the biofilm (see Fig. 3.16), and pollutant loading rates. Fugacity is the propensity of a compound to be released from one physical stage to another. For example, Henry's Law states that a substances potential to flee from liquid phase to the gas stage is a function of its vapor pressure and aqueous solubility. Care must be taken in monitoring porous media for incomplete biodegradation, the presence of substances that may be toxic to the microbes, excessive concentrations of organic acids and alcohols, and pH. The system should also be checked for shock and the presence of dust, grease, or other substances that may clog the pore spaces of the media.[21]

Figure 3.16 Biofiltration without a liquid phase used to treat vapor-phase pollutants. Air carries the volatilized contaminants upward through a porous medium (e.g., compost) containing microbes acclimated to break down the particular contaminants. The wastes at the bottom of the system can be heated to increase partitioning to the gas phase. Microbes in the biofilm surrounding each compost particle metabolize the contaminants into simpler compounds, eventually converting them into carbon dioxide and water vapor.



The key is understanding the scientific basis of any design. In these technologies, the physics, chemistry, and biology dictate success and failure in green systems.

Pollution Prevention

Our discussion of treatment control prompts the question: "Why not prevent pollution in the first place?" The U.S. Environmental Protection Agency (EPA) defines *pollution prevention* as "The use of materials, processes, or practices that reduce or eliminate the creation of pollutants or wastes at the source. It includes practices that reduce the use of hazardous materials, energy, water or other resources and practices that protect natural resources through conservation or more efficient use."[22] Thus, to prevent pollution we must think about how to eliminate the waste, regardless of how this might be done.

Originally, pollution prevention was applied to industrial operations with the idea of reducing either the amount of the wastes being produced or to change their characteristics in order to make them more readily disposable. Many industries changed to water-soluble paints, for example, thereby eliminating organic solvents, cleanup time, and so on, and often ended up saving considerable money. In fact, the concept was introduced as "pollution prevention pays," emphasizing that many of the changes would actually save money. In addition, the elimination or reduction of hazardous and otherwise difficult wastes also has a long-term effect—it reduces the liability a company carries as a consequence of its disposal operations.

With the passage of the Pollution Prevention Act of 1990, the EPA was directed to encourage pollution prevention by setting appropriate standards for pollution prevention activities, assisting federal agencies in reducing wastes generated, working with industry to promote the elimination of wastes by creating waste exchanges and other programs, seeking out and eliminating barriers to the efficient transfer of potential wastes, and doing this with the cooperation of the states.

In general, the procedure for the implementation of pollution prevention activities is to (1) recognize a need, (2) assess the problem, (3) evaluate the alterative, and (4) implement the solutions. Contrary to most pollution control activities, industries generally have welcomed this governmental action, recognizing that pollution prevention can and often does result in the reduction of costs to the industry. Unlike many regulatory mandates, where it is in the company's best financial interests not to recognize that a rule applies to them, the need to avoid generating wastes quite often is internal and the company seeks to initiate the pollution prevention procedure. During the assessment phase, a common procedure is to perform a *waste audit*, which is actually a black box mass balance, using the company as the black box.

Example: Waste Audit

A manufacturing company is concerned about air emissions of volatile organic carbons. These chemicals can volatilize during the manufacturing process, but the company is not able to estimate accurately the rate of volatilization, or even which chemicals are partitioning to the vapor phase. The company conducts an audit of three of their most widely used volatile organic chemicals, with the following results:

Purchasing department records:

Material	Purchase Quantity (barrels)
Carbon tetrachloride[a] (CCl_4)	48
Methyl chloride[b] (CH_2Cl_3)	228
Trichloroethylene (C_2HCl_3)	505

[a] The correct name is tetrachloromethane, but the compound was in such common use throughout the twentieth century, referred to as carbon tetrachloride, that the name is still used frequently in the engineering and environmental professions.

[b] Also known as chloromethane.

Wastewater treatment plant influent:

Material	Average Concentration (mg L^{-1})
Carbon tetrachloride	0.343
Methylene chloride	4.04
Trichloroethylene	3.23

The average influent flow rate to the treatment plant is 0.076 $m^3\ s^{-1}$.

Hazardous waste manifests (what leaves the company by truck headed to a hazardous waste treatment facility):

Material	Barrels	Concentration (%)
Carbon tetrachloride	48	80
Methyl chloride	228	25
Trichloroethylene	505	80

Unused barrels at the end of the year:

Material	Barrels
Carbon tetrachloride	1
Methyl chloride	8
Trichloroethylene	13

How much VOC is escaping?

Solution: Conduct a black box mass balance:

$$[A_{acc}] = [A_{in}] - [A_{out}] + [A_{prod}] - [A_{cons}]$$

where

A_{acc} = mass of A per unit time accumulated
A_{in} = mass of A per unit time in
A_{out} = mass of A per unit time out
A_{prod} = mass of A per unit time produced
A_{cons} = mass of A per unit time consumed

The materials A are, of course, the three VOCs.

Barrels must be converted to cubic meters, and the density of each chemical must be known. Each barrel is 0.12 m^2, and the density of the three chemicals is 1548, 1326, and 1476 kg m^{-3}. The mass per year of carbon tetrachloride accumulated is

$$[A_{acc}] = 1\ \text{barrel/yr} \times 0.12\ \text{m}^3/\text{bbl} \times 1548\ \text{kg m}^{-3} = 186\ \text{kg yr}^{-1}$$

Similarly,

$$[A_{in}] = 48 \times 0.12 \times 1548 = 8916\ \text{kg yr}^{-1}$$

The mass out is in three parts: the mass discharged to the wastewater treatment plant, the mass leaving on the trucks to the hazardous waste disposal facility, and the mass volatilizing. So

$$\begin{aligned}[A_{out}] &= [0.343\ \text{gm}^{-3} \times 0.076\ \text{m}^3\ \text{s}^{-1} \times 86400\ \text{s day}^{r\,-1} \times 365\ \text{days yr}^{-1} \\ &\quad \times 10^{-3}\ \text{kg g}^{-1}] + [48 \times 0.12 \times 1548 \times 0.80] + A_{air} \\ &= 822.1 + 7133 + A_{air}\end{aligned}$$

where A_{air} is the mass per unit time emitted to the air. Since no carbon tetrachloride is consumed or produced,

$$186 = 8916 - (822.1 + 7133 + A_{air}] + 0 - 0$$

and $A_{air} = 775$ kg yr^{-1}.

If a similar balance is performed for the other chemicals, it appears that the loss to air of methyl chloride is about 16,000 kg yr^{-1} and that of trichloroethylene is about 7800 kg yr^{-1}.

If the intent is to cut total VOC emissions, clearly the first target should be the methyl chloride, at least in terms of the mass released. But another important consideration in preventing pollution is *relative risk*.

Although methyl chloride is two orders of magnitude more volatile than the other pollutants, all three compounds are likely to be found in the atmosphere. Thus, inhalation is a likely exposure pathway.

Since risk is the product of exposure times hazard ($R = E \times H$), we can compare the risks by applying a hazard value (e.g., cancer potency). We can use the air emissions calculated above as a reasonable approximation of exposure via the inhalation pathway,* and the inhalation cancer slope factors can be used to represent the hazard. These slope factors are published by the U.S. EPA and are found to be:

$$\begin{aligned}&\text{carbon tetrachloride}: 0.053\ \text{kg day mg}^{-1}\\&\text{methyl chloride}: 0.0035\ \text{kg day mg}^{-1}\\&\text{trichloroethylene}: 0.0063\ \text{kg day mg}^{-1}\end{aligned}$$

The relative cancer risk for the three compounds can be estimated by removing the units (i.e., we are not actually calculating the risk, only comparing the three compounds against each other, so we do not need units. If we were calculating risks, the units for exposure would be mass of contaminant per body mass per time (e.g., mg kg^{-1} day^{-1}), whereas the slope factor unit is the inverse of this (i.e., kg · day · mg^{-1}), so risk itself is a unitless probability.

$$\begin{aligned}&\text{carbon tetrachloride}: 0.053 \times 775 = 41\\&\text{methyl chloride}: 0.0035 \times 16000 = 56\\&\text{trichloroethylene}: 0.0063 \times 7800 = 49\end{aligned}$$

Thus, in terms of relative risk, methyl chloride is again the most important target chemical, but the other two are much closer. In fact, given the uncertainties and assumptions, from a relative risk perspective, the importance of the removing the three compounds is nearly identical, owing to the much higher cancer potency of CCl_4.

Source: D. A. Vallero and P. A. Vesilind, *Socially Responsible Engineering: Justice in Risk Management,* Wiley, Hoboken, NJ, 2006.

*Even without calculating the releases, it is probably reasonable to assume that the exposures will be similar since the three compounds have high vapor pressures (more likely to enter the vapor phase and to be inhaled): carbon tetrachloride, 115 mm Hg; methyl chloride, 4300 mmHg; and trichloroethylene, 69 mmHg.

After identifying and characterizing the environmental problems, the next step is to discover useful options. These options fall generally into three categories: (1) operational changes, (2) materials changes, and (3) process modifications.

Operational changes might consist simply of better housekeeping: plugging up leaks, eliminating spills, and so on. A better schedule for cleaning, and segregating the water might similarly yield a large return on a minor investment. Also, as our waste audit example demonstrates, less mass translates directly into less risk.

Materials changes often involve the substitution of one chemical for another which is less toxic or requires less hazardous materials for cleanup. The use of trivalent chromium (Cr^{3+}) for chrome plating instead of the much more toxic hexavalent chrome has found favor, as has the use of water-soluble dyes and paints. In some instances, ultraviolet radiation has been substituted for biocides in cooling water, resulting in better-quality water and no waste cooling water disposal problems. In one North Carolina textile plant, biocides have been used in air washes to control algal growth. Periodic "blowdown" and cleaning fluids had been discharged to the stream, but this discharge proved toxic to the stream and the state of North Carolina revoked the plant's discharge permit. The town would not accept the waste into its sewers, rightly arguing that this might have serious adverse effects on its biological wastewater treatment operations. The industry was about to shut down when it decided to try ultraviolet radiation as a disinfectant in its air wash system. Happily, they found that the ultraviolet radiation effectively disinfected the cooling water and that the biocide was no longer needed. This not only eliminated the discharge but eliminated the use of biocides all together, thus saving the company money. The payback was 1.77 years.[23] That is, in less than two years the conversion paid for itself, so that each following year the profits were added to the company's bottom line.

Process modifications usually involve the greatest investments and can result in the most rewards. For example, a countercurrent wash water use instead of a once-through batch operation can significantly reduce the amount of wash water needing treatment, but such a change requires pipes, valves, and a new process protocol. In industries where materials are dipped into solutions, such as in metal plating, the use of drag-out recovery tanks, an intermediate step, has resulted in a savings in the plating solution and reduction in the waste generated.

Pollution prevention has the distinct advantage over stack controls that most of the time a company not only eliminates or greatly reduces the release of hazardous materials but also saves money. Such savings are in several forms, including, of course, direct savings in processing costs, as in the ultraviolet disinfection example above. The most obvious costs are those normally documented in company records, such as direct labor, raw materials, energy use, capital equipment, site preparation, tie-ins, employee training, and regulatory recordkeeping (e.g., permits).[24] In addition, there are other savings, including those resulting from not having to spend time on submitting compliance permits and suffering potential

Table 3.9 Pollution Cost Categories

Cost Category	Typical Cost Components
Usual/normal	Direct labor
	Raw materials
	Energy and fuel
	Capital equipment and supplies
	Site preparation
	Tie-ins
	Training
	Permits: administrative and scientific
Hidden or direct	Monitoring
	Permitting fees
	Environmental transformation
	Environmental impact analyses and assessments
	Health and safety assessments
	Service agreements and contracts
	Legal
	Control instrumentation
	Reporting and record keeping
	Quality assurance planning and oversight
Future liabilities	Environmental cleanup, removal, and remedial actions
	Personal injury
	Health risks and public insults
	More stringent compliance requirements
	Inflation
Less tangible	Consumer reaction and loss of investor confidence
	Employee relations
	Lines of credit (establishing and extending)
	Property values
	Insurance premiums and insurability
	Greater regulatory oversight (frequency, intensiveness, onus)
	Penalties
	Rapport and leverage with regulators

Source: Adapted from N. P. Cheremisinoff, *Handbook of Solid Waste Management and Waste Minimization Technologies*, Butterworth-Heinemann, Woburn, MA, 2003.

fines for noncompliance. Future liabilities weigh heavily where hazardous wastes have to be buried or injected. Additionally, there are the intangible benefits of employee relations and safety (see Table 3.9).

In many ways, the transition from command-and-control approaches to prevention has been incremental: an evolution rather than a revolution. Regulatory requirements and good engineering practice will continue to call for better approaches in both areas. Control technologies and pollution prevention are not separate endeavors. In fact, the life-cycle view prohibits such dichotomies. They are both crucial tools in green design. The advances will continue toward sustainability and beyond. By focusing on the function and eliminating inefficiencies, we can expect even better results. We should not be content with sustaining existing methods. Engineers and other designers are dedicated to continuous improvement and total quality. As such, we should expect to approach regenerative strategies for design, manufacturing, use, and reuse.

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of state and local agencies. However, it behooves all professionals to collaborate, hopefully before any land is purchased and contractors are retained. Councils of government (COGs) and other "A-95" organizations can be rich resources when considering options on siting. They can help avoid the need for problems long before implementation, to say nothing of contentious zoning appeal and planning commission meetings and perception problems at public hearings. Accessibility to services is attractive, but the adverse aspects of facilities providing the services, e.g. adors and noise near a factory, are likely to be avoided by the public.

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chapter 4

Place and Time

> It is our aspiration that engineers will continue to be leaders in the movement toward the use of wise, informed, and economical sustainable development. This should begin in our educational institutions and be founded in the basic tenets of the engineering profession and its actions.
>
> National Academy of Engineering[1]

The terms *green engineering*, *green architecture*, and *sustainable design* are often linked in the literature. Among the common themes is the concern about space. Although the various design professions approach spatial concepts in different ways, they all work within a particular sphere of influence, bounded by space.

Environmental conscientiousness evolved in the twentieth century from a peculiar interest of a few design professionals to an integral part of every engineering disciple. In fact, one of the most important macroethical challenges for engineers is to provide more sustainable designs. Recall that the U.S. Environmental Protection Agency defines *green engineering* as "the design, commercialization and use of processes and products that are feasible and economical while reducing the generation of pollution at the source and minimizing the risk to human health and the environment."[2] Green engineering asks the designer to incorporate "environmentally conscious attitudes, values, and principles, combined with science, technology, and professional engineering practice, all directed toward improving local and global environmental quality."[3] However, the design must also be feasible and must adhere to the first canon of engineering practice: holding paramount the safety, health, and welfare of the public. One of the principles of "green engineering" is recognition of the importance of *sustainability*.

THERMODYNAMICS OF TIME AND SPACE

In our introduction to the physics of green design, we introduced a number of thermodynamic concepts. All engineering disciplines must be grounded in thermodynamics, but chemical engineers are arguably those who deal with it incessantly. It should not come as a surprise that chemical engineering has been a leader in green approaches. After all, “chemical engineering is a broad discipline dealing with processes (industrial and natural) involving the transformation (chemical, biological, or physical) of matter or energy into forms useful for mankind, economically and without compromising environment, safety, or finite resources.”[4] In fact, chemical engineering’s central integrating theme is the reactor. In the reactor we can visualize mass and energy balances. Thus, it is impossible to think about a design without making use of chemical engineering concepts.

The reactors that most chemical engineers work with are at the industrial scale. This, of course, includes tanks and vats that have certain materials and energy that enters and certain, but different, forms and amounts of materials and energy that leave. In environmental engineering, these thermodynamic behaviors also occur but over a widely diverse domain, at scales ranging from subcellular to global (see Fig. 4.1). For example, the processes that lead to a contaminant

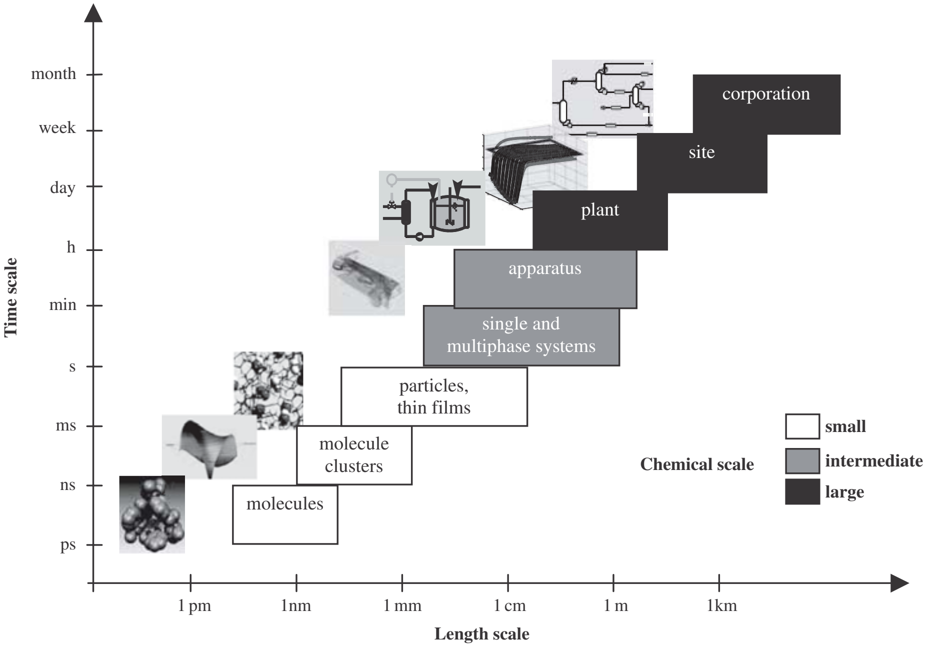


Figure 4.1 Scales and complexities of reactors.

Note: ms, millisecond; ns, nanosecond; ps, picosecond.

Adapted from W. Marquardt, L. von Wedel, and B. Bayer, “Perspectives on lifecycle process modeling,” in *Foundations of Computer-Aided Process Design*, M. F. Malone, J. A. Trainham, and B. Carnahan, Eds., *AIChE Symposium Series 323*, Vol. 96, 2000, pp. 192–214.

moving and changing in a bacterium may be very different from processes at the lake or river scale, which in turn are different from processes that affect a contaminant as it crosses the ocean. This is simply a manifestation of the first law of thermodynamics: Energy or mass is neither created nor destroyed, only altered in form. This also means that energy and mass within a system must be in balance: What comes in must equal what goes out. Engineers measure and account for these energy and mass balances within a region in space through which a fluid travels. Recall from Chapter 2 that such a region is known as a *control volume* and that the control volumes where these balances occur can take many forms. Figure 2.3 illustrates several ways in which mass balances (reactors) apply to environmental processes. So within any control volume, one can calculate the balance. Mass balance, for example, is

$$\begin{bmatrix} \text{quantity of} \\ \text{mass per unit volume} \\ \text{in a medium} \end{bmatrix} = [\text{total flux of mass}] + \begin{bmatrix} \text{rate of production or loss} \\ \text{of mass per unit volume} \\ \text{in a medium} \end{bmatrix} \tag{4.1}$$

or, stated mathematically,

$$\frac{dM}{dt} = M_{\text{in}} - M_{\text{out}} \tag{4.2}$$

where M is the mass and t is the specified time interval. If we are concerned about a specific chemical (e.g., environmental engineers worry about losing good ones such as oxygen, or forming bad ones such as the toxic dioxins), we would need to add a reaction term (R):

$$\frac{dM}{dt} = M_{\text{in}} - M_{\text{out}} \pm R \tag{4.3}$$

However, within these reactors are smaller-scale reactors (e.g., within a fish liver, on a soil particle, in the pollutant plume or a forest, as shown in Fig. 4.2). Thus, scale and complexity can vary by orders of magnitude. So the bottom line is that green engineering must make use of the tools that chemical engineers provide, especially the thermodynamics of mass and energy balances.

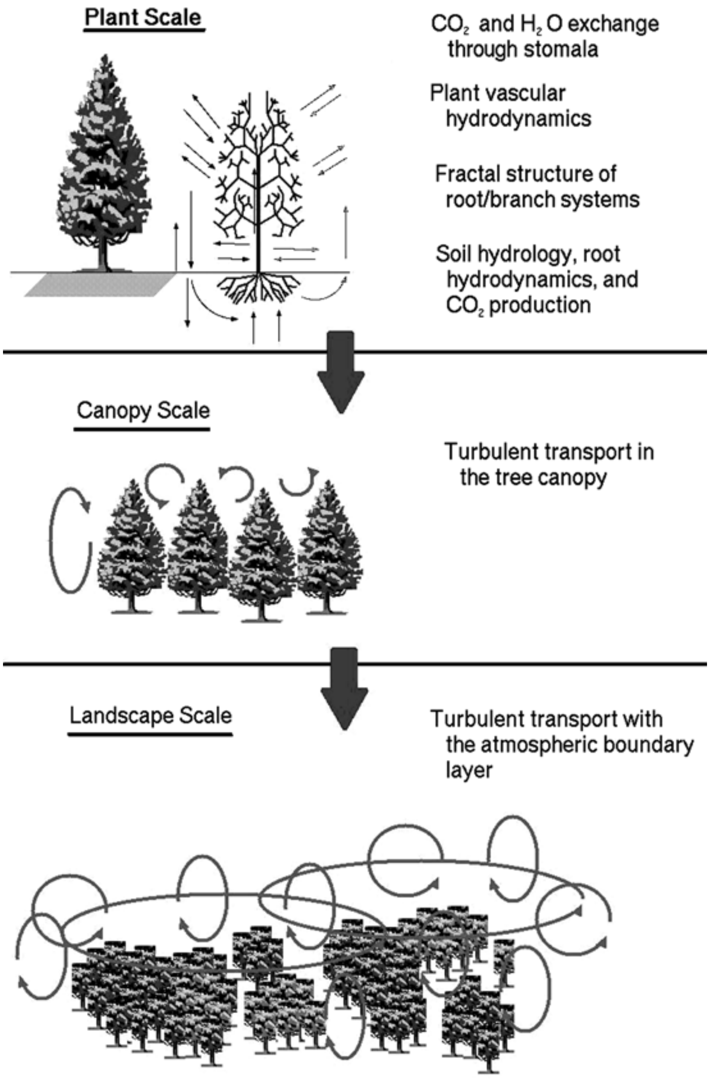


Figure 4.2 Three heirarchical scales applied to trees. Although the flow and transport equations do not change, the application of variables, assumptions, boundary conditions, and other factors are scale- and time-dependent.

Adapted from G. Katul, "Modeling heat, water vapor, and CO_2 transfer across the biosphere–atmosphere interface," seminar presentation at Pratt School of Engineering, Research Triangle Park, NC, December 1, 2001.

Sidebar: Green Is Not Junk Science

Green engineering is comprised of myriad possibilities in how to apply the sciences, but the way these sciences are applied changes with new needs. The basic sciences seldom have to deal with new paradigms. Most of what chemists needed to know in 1980 still holds. This is not the case for green engineering. The problems have changed in scope and scale, but they have also changed in kind. Also, as we have made progress in solving some of the biggest environmental problems, we have uncovered and encountered more intractable ones. For example, in the 1970s we were fairly happy to see most effluent (sewage) from towns and cities meet standards of 20 parts per million (ppm) suspended solids and 20 ppm biochemical oxygen demand (called *secondary standards*), but now we worry about certain pesticides and heavy metals in the parts per billion (ppb) range or lower.

This brings to mind a problem not so much for green design as for environmental "science." It seems that when environmental awareness began to gain prominence after the 1960s, some universities began to recast their science and policy programs as "environmental." So one began to see new programs and departments in environmental policy, environmental studies, environmental biology, and later, environmental chemistry, environmental geography, and even environmental physics. This often happens when a subject gains currency. Some of this overinclusiveness may be because it is thought to be easier to compete for grants or to attract students, but sometimes there are very small changes beyond the new adjective in front of the department name. Even worse, in an attempt to address the political and social import of environmental problems, some programs were built with little scientific rigor. Students could graduate in "environmental studies" or even "environmental science" without much scientific and mathematical underpinning.

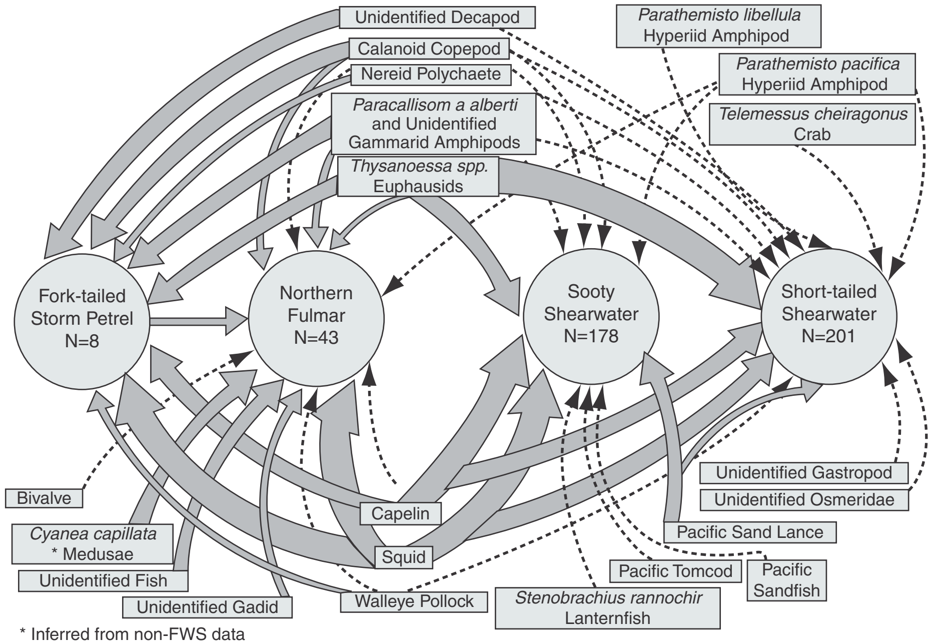
This is not to say that environmental problems are not complex and should not be addressed from social scientific and even humanities perspectives. They definitely should. But rigorous science should never be sacrificed. For an environmental problems course, Vallero was recently asked to use a textbook that included *no* equations. This did not occur at Duke University, where the engineering faculty are free to choose textbooks and reading materials. Most instructors augment texts with their own information, including math and science, but it is troubling that a 650-page text would contain only descriptive information about environmental problems without any calculations. The review questions (i.e., homework) were for the most part open-ended "consciousness-raising" probes, not recitations. Questions include queries like why reintroducing species might be controversial or what role a certain politician had in legislation. These are interesting and even important, but they are no substitute for technical questions to advance the understanding why or if a chemical contaminant is actually going to cause an environmental problem. Students may learn names and dates and expound complex political theory about environmental problems and their needed solutions, but they risk lacking insight into the most fundamental aspects of thermodynamics and other physicochemical characteristics of these problems. This should be of concern to the general public, who expects its professionals to understand the science and that any arguments being made are grounded in first principles.

The point is that we must be careful that this "advocacy science" or, in its worst form, "junk science" does not find its way into green engineering. There is a canon that is common in most engineering codes that tells us that we need to be "faithful agents." This, coupled with an expectation of competency, requires us to be faithful to the first principles of science. In a way, pressures from clients and political or ideological correctness could tempt the next generation of engineers to try to "repeal Newton's laws" in the interest of certain influential groups! This is not to say that engineers will have the luxury to ignore the wishes of such groups, but since we are the ones with our careers riding on these decisions, we must clearly state when an approach is scientifically unjustifiable. We must be good listeners, but also honest arbiters.

Unfortunately, many scientific bases for decisions are not nearly as clear as Newton's laws. They are far removed from first principles. For example, we know how fluids move through conduits (with thanks to Bernoulli, Navier, Stokes, et al.), but other factors come into play when we estimate how a contaminant moves through very small vessels (e.g., intercellular transport). The combination of synergies and antagonisms at the molecular and cellular scales makes for uncertainty. Combining this with uncertainties about the effects of enzymes and other catalysts in the cell and even greater uncertainties and possible errors are propagated. So the engineer operating at the mesoscale (e.g., a wastewater treatment plant) can be fairly confident about the application of first principles of contaminant transport, but the biomechanical engineer looking at the same contaminant at the nanoscale is not as confident. That is where junk science sometimes is able to raise its ugly head. In the void of certainty (e.g., at the molecular scale), some untenable arguments are made about what does or does not happen. This is the stuff of infomercials. The new engineer had better be prepared for some off-the-wall ideas of how the world works. New hypotheses for causes of cancer, or even etiologies of cancer cells, will be put forward. Most of these will be completely unjustifiable by physical and biological principles, but they will appear sufficiently plausible to the unscientific.

The challenge of the green engineer will be to sort through this morass without becoming closed-minded. After all, many scientific breakthroughs were considered crazy when proposed (recalling Copernicus, Einstein, Bohr, and Hawking, to name a few). But even more really were wrong and upon scientific scrutiny, were unsupportable.

From an integrated, green viewpoint, a design must incorporate an appreciation for the interrelationships of the abiotic (nonliving) and biotic (living) environments. We may have not known it, but we have been taking advantage of the concept of *trophic state* for much of our history. Organisms, including humans,



* Inferred from non-FWS data

Figure 4.3 Flow of energy and mass among invertebrates, fish, and seabirds (*Procellariform*) in the Gulf of Alaska. The larger the width of the arrow, the greater the relative flow. Note how some species prefer crustaceans (e.g., copepods and euphausiids), but other species consume larger forage species, such as squid.

From G. A. Sanger, *Diets and Food Web Relationships of Seabirds in the Gulf of Alaska and Adjacent Marine Areas*, OCSEAP Final Report 45, U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Washington, DC, 1983, pp. 631–771.

live within an interconnected network or web of life (see Fig. 4.3). In a way this is not any different from the energy and mass budgets of the chemical reactors familiar to chemical engineers. Of course, living things are more complex and complicated, but that is something to which any successful environmental engineer will have to adapt. For example, the ecologist may be perfectly happy to understand the complex interrelationships shown in Figure 4.4, but in the event of designing an offshore oil rig or following an oil spill, the design engineer must append this web to another system that shows humans as consumers. Also, the rig or the spill may change the abundance and richness of species, so the entire web is changed. Regulations are merely floors and ceilings of good engineering design. For example, despite compliance with environmental regulations, biological populations are declining as a result of residual stresses from a number of drivers, including:

- Land-use change
- Resource extractions
- Chemical pollutants
- Exotic invasive species
- Climate change

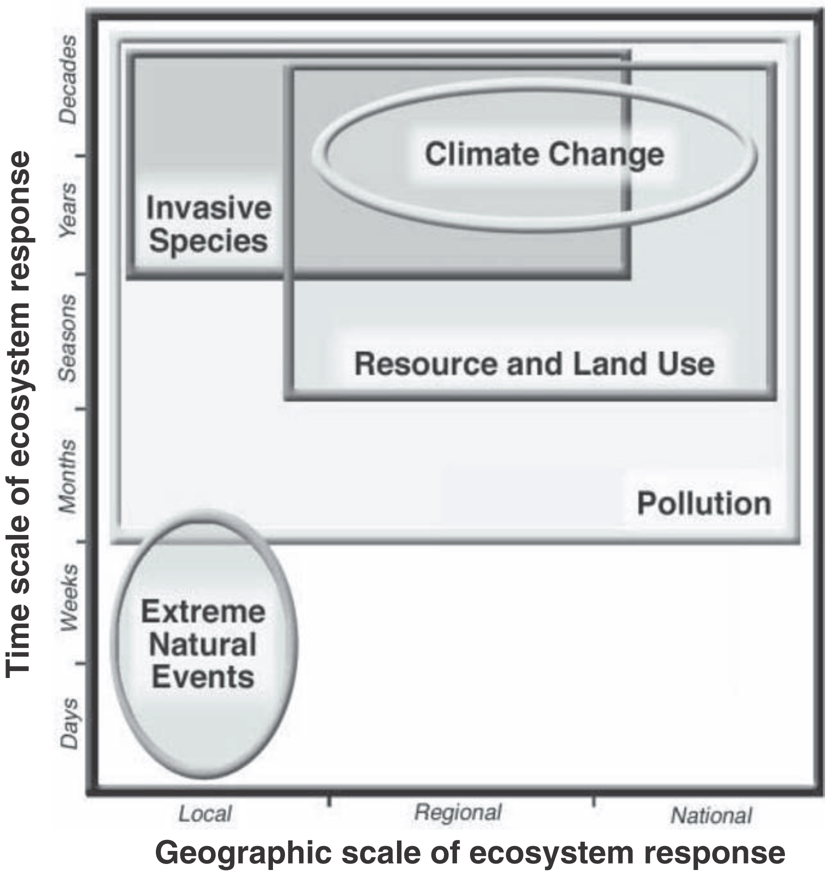


Figure 4.4 The response to stressors has temporal and spatial dependencies. Near-field stressors can result from a spill or emergency situation. At the other extreme, global climate change can result from chronic releases of greenhouse gases with expansive (planetary) impacts if global temperatures rises significantly.

From R. Araujo.

The "feedbacks" in Figure 4.3 are the stuff of green engineering. The engineer will be called upon to optimize the constructed project and to preserve (limit the effects on) the energy and mass balances. Sometimes, the environmental engineer must decide that there is no way to optimize both. In this instance, the engineer must recommend the "no build" option. Usually, though, the designer must help the client navigate through numerous permutations and optimize solutions from more than two variables (e.g., species diversity, productivity and sustainability, costs and feasibility, oil extraction efficiencies).

SOIL: THE FOUNDATION OF SUSTAINABLE SITES

Good design requires an understanding of soil. Soil is an example of a system comprised of abiotic and biotic components. Traditionally, engineers have been concerned principally with soil mechanics, particularly such aspects as gel strength and stability, so that it serves a sufficient underpinning for structural foundations and footings. They are also concerned about drainage, compaction, shrink–swell characteristics, and other features that may affect building site selection.

Soil is classified into various types. For many decades, soil scientists have struggled with uniformity in the classification and taxonomy of soil. Much of the rich history and foundation of soil scientists has been associated with agricultural productivity. The very essence of a soil's "value" has been its capacity to support plant life, especially crops. Even forest soil knowledge owes much to the agricultural perspective, since much of the reason for investing in forests has been monetary. A stand of trees are seen by many to be a *standing crop*. In the United States, for example, the National Forest Service is an agency of the U.S. Department of Agriculture. Engineers have been concerned about the statics and dynamics of soil systems, improving the understanding of soil mechanics so that they may support, literally and figuratively, the built environment. The agricultural and engineering perspectives have provided valuable information about soil that green designers can put to use. The information is certainly necessary, but not completely sufficient, to understand how pollutants move through soils, how the soils themselves are affected by the pollutants (e.g., loss of productivity, diversity of soil microbes), and how the soils and contaminants interact chemically (e.g., changes in soil pH will change the chemical and biochemical transformation of organic compounds). At a minimum, environmental scientists must understand and classify soils according to their texture or grain size (see Table 4.1), ion-exchange capacities, ionic strength, pH, microbial populations, and soil organic matter content.

Whereas air and water are fluids (see Chapter 2), *soil* is a matrix made up of various components, including organic matter and unconsolidated material.

Table 4.1 Commonly Used Soil Texture Classifications

Name	Size Range (mm)
Gravel	> 2.0
Very coarse sand	1.0–1.999
Coarse sand	0.500–0.999
Medium sand	0.250–0.499
Fine sand	0.100–0.249
Very fine sand	0.050–0.099
Silt	0.002–0.049
Clay	< 0.002

Source: T. Loxnachar, K. Brown, T. Cooper, and M. Milford, *Sustaining Our Soils and Society*, American Geological Institute, Soil Science Society of America, and USDA Natural Resource Conservation Service, Washington, DC, 1999.

In water systems, sediment has the same type of matrix. The matrix contains liquids (*substrate* to the chemist and engineer) within its interstices. Much of the substrate of this matrix is water with varying amounts of solutes. As a general rule, sediment is more highly saturated with water than are soils. However, some soils can be permanently saturated, such as the muck in wetlands.

At least for most environmental conditions, air and water are solutions of very dilute amounts of compounds. For example, air's solutes represent small percentages of the solution at the highest level (e.g., water vapor) and most other solutes represent parts per million (a bit more than 300 ppm of carbon dioxide). Thankfully, most "contaminants" in air and water are in the parts per billion range. On the other hand, soil and sediment themselves are conglomerations of all states of matter.

Soil is predominantly solid but frequently has large fractions of liquid (soil water) and gas (soil air, methane, carbon dioxide) that make up the matrix. The composition of each fraction is highly variable. For example, soil gas concentrations are different from those in the atmosphere and change profoundly with depth from the surface. Table 4.2 shows the inverse relationship between carbon dioxide and oxygen. Sediment is a collection of particles that have settled on the bottom of water bodies.

Ecosystems are combinations of these media. For example, a wetland system consists of plants that grow in soil, sediment, and water. The water flows through living and nonliving materials. Microbial populations live in the surface water, with aerobic species congregating near the water surface and anaerobic microbes increasing with depth due to the decrease in oxygen levels caused by the reduced conditions. Air is not only important at the water and soil interfaces but is a vehicle for nutrients and contaminants delivered to the wetland. The groundwater is fed by the surface water during high-water conditions and feeds the wetland during low water.

Table 4.2 Composition (% Volume of Air) of Two Important Gases in Soil Air

	Silty Clay		Silty Clay Loam		Sandy Loam	
Depth from Surface (cm)	O_2	CO_2	O_2	CO_2	O_2	CO_2
30	18.2	1.7	19.8	1.0	19.9	0.8
61	16.7	2.8	17.9	3.2	19.4	1.3
91	15.6	3.7	16.8	4.6	19.1	1.5
122	12.3	7.9	16.0	6.2	18.3	2.1
152	8.8	10.6	15.3	7.1	17.9	2.7
183	4.6	10.3	14.8	7.0	17.5	3.0

Source: V. P. Evangelou, *Environmental Soil and Water Chemistry: Principles and Applications*, Wiley, New York, 1998.

So another way to think about these environmental media is that they are compartments, each with boundary conditions, kinetics, and partitioning relationships within a compartment or among other compartments. Chemicals, whether nutrients or contaminants, change as a result of the time spent in each compartment. The green designer's challenge is to describe, characterize, and predict the behaviors of various chemical species as they move through the media.

Soil bacteria and fungi are particularly adaptable to highly concentrated waste environments, such as those in wastewater treatment tanks and hazardous waste reactors. Most university environmental engineering programs now have a cadre of experts in microbiology and biochemistry. Even those in the more physical realms of environmental engineering, such as system design, ultraviolet and ozonization disinfection controls, and exposure assessment, have a working knowledge of microbiology. This will undoubtedly increase in the decades ahead. When something is amiss, the cause and cure lie within the physics, chemistry, and biology of the system. It is up to the professionals to apply the principles properly.

The eminent engineer Ross McKinney has constantly reminded us to look under our feet for answers to the most perplexing environmental problems. He was talking about using soil bacteria to break down even the most recalcitrant pollutants. But he was also reminding us that engineers are highly creative people. As another pioneer in environmental engineering, AarneVesilind, often says, engineers "do things."[5] Both McKinney and Vesilind are telling us that in the process of our doing things, we should be observant to new ways of doing those things. The answer can be right under our feet.

Green design presents something of a paradox to engineers. We do not want to expose our clients or ourselves to unreasonable risks, but we must to some extent "push the envelope" to find better ways of doing this, so we tend to suppress new ways of looking at problems. However, facts and theories may be so overwhelmingly convincing that we must change our world view. Thomas S. Kuhn refers to this as a *paradigm shift*.[6] Scientists are often very reluctant to accept these new ways of thinking (Kuhn said that such resistance can be "violent"). In fact, even when we do accept them, they are often not dramatic reversals (revolutions) but modifications of existing designs (evolutions). Some say that the bicycle was merely a mechanically re-rendering of the horse (e.g., the saddle seat, the linear and bilaterally symmetrical structure, the harness-like handle bars), as was the automobile.

Integrating the advice of Kuhn, McKinney, and Vesilind leads to something akin to: "Yes, go with what works, but be aware of even the most subtle changes in what you are doing today versus what you did successfully yesterday. And do not disregard the importance of common sense and rationality in green design." The answers are often readily available, cheap, and feasible, but it takes some practice and a willingness to admit that there *is* a better way to do it.

McKinney's advice that we look under our feet also tells us that natural systems are our allies. I believe that this observation, which may be intuitively obvious to this generation of environmental engineers, was not fully accepted in the 1950s and 1960s. In fact, there was a growing preference toward abiotic chemical solutions as opposed to biological approaches. Recall that there was a petrochemical revolution following World War II. Modern society at that time placed a premium on synthetic, plastic solutions. Toward the end of the decade of the 1960s, the concept of using "*passé*" techniques such as acclimated bacteria to treat wastes was increasingly seen as "old fashioned." We needed a miracle chemical to do this in less time and more efficiently. Interestingly, Vallero also had a few conversations with McKinney about the then-nascent area of genetic engineering, and if memory serves, he showed the same skepticism that he did for that of abiotic chemistry as the new paradigm. In a sense, McKinney argued that engineers had been doing "genetic engineering" all along and that we should be wary of the sales pitches for new "supergenes." Again, I believe that he has been proven generally correct, although he would be among the first to use an organism that would do a better job, no matter whether it was achieved through natural acclimation or through contemporary genetic engineering.

GREEN ARCHITECTURE AND THE SENSE OF PLACE

Architecture and engineering have gone through numerous transitions over the past two centuries. In the West, these have tracked with changes in societal norms and expectations. A large change has occurred in how we perceive the world around us. *Green architecture* has been defined as the means of allowing

> people to become more in touch with the environment in which they live. It incorporates natural landscapes into the buildings design which gives people a better connection to the land. It also takes into account of all the environmental effects which a building will have on a place. Green design is based out of creating buildings which fit into their natural surrounds and give the people who use them a sense of place, as opposed to conventional architecture which pushes people away from the natural environment. Many of the key components of green design involve in-depth knowledge about a place. Green buildings must account for sun intensities, temperature variation, precipitation and many other environmentally driven aspects. Without knowledge of local environments, green buildings cannot plan for variations and they will not be as energy efficient.[7]

Green buildings incorporate given site characteristics and conditions, such as microclimate, light exposure, vegetation, and urban factors (e.g., noise, amenities) into the design. Thus, the building is seen as an entity that goes beyond mere shelter to become a "selective filter" against outside interferences and admitting desirable qualities (e.g., incoming solar radiation in the winter, daylight, and air exchanges).[8]

Thus, green architecture embodies a sense of place that differs from that of the "endless frontier" of the eighteenth, nineteenth, and much of the twentieth centuries, where individualism and conquest led to buildings that optimized isolation *from* the environment rather than optimization *of* the environment. In the former sense of place, the environment was easily viewed as inexhaustible and ever resilient. Whereas green architecture often starts with a view of the potential building, the canvas of the environment is the real starting point. Using the common art analogy, the building site canvas is certainly not empty as many earlier designers perceived the site to be. It is actually quite full, and any change must account for the effect that a building or planned community will have on this environment. One of the first to articulate this new sense of place was Aldo Leopold, whose ideas we discuss next.

Pruitt-Igoe: Lessons from the Land Ethic in 21st-Century Design

Environmental ethics is the set of morals (i.e., those actions held to be right or to be wrong) in how people interact with the environment. Three ethical viewpoints dominate environmental ethics: anthropocentrism, biocentrism, and ecocentrism (see Fig. 4.5). *Anthropocentrism* is a philosophy or decision framework based on

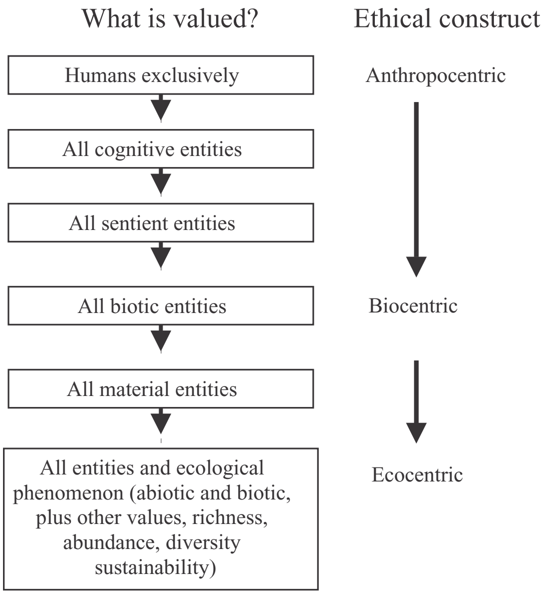


Figure 4.5 Continuum of ethical viewpoints.

Adapted from R. B. Meyers, "Environmental values, ethics and support for environmental policy: a heuristic, and psychometric instruments to measure their prevalence and relationships," Presented at the International Conference on Civic Education Research, New Orleans, LA, November 16–18, 2003.

human beings. It is the view that all humans (and only humans) have moral value. Nonhuman species and abiotic resources have value only in respect to that associated with human values (known as *instrumental value*). Conversely, *biocentrism* is a systematic and comprehensive account of moral relationships between humans and other living things. The biocentric view requires an acceptance that all living things have inherent moral value, so that respect for nature is the ultimate moral attitude. By extension of the biocentric view, *ecocentrism* is based on the entire ecosystem rather than a single species.

Thus, from the standpoint of perceived value, anthropocentrists may strongly disagree with biocentrists on the loss of animal habitat. The anthropocentrist may hold that the elimination of a stand of trees is necessary, so they provide less perceived monetary worth (instrumental value) than the project in need of clear-cutting, whereas the biocentrist sees the same stand of trees has having sufficient inherent value to prevent the clear-cutting. Few hold any of these viewpoints exclusively, but apply them selectively. For example, a politician holding a strong anthropocentric viewpoint on medical research or land development may love animals as pets.

In his seminal journal *A Sand County Almanac* (1949),[9] Aldo Leopold took the ecocentric view and established the *land ethic*. It was a dramatic shift in thinking from that which dominated the first half of the twentieth century. Leopold held that this new ethic "reflects the existence of an ecological conscience, and this in turn reflects a conviction of individual responsibility for the health of land." This is a precursor to ecocentrism.

The ecocentric view asks the designer to perceive undeveloped land or existing structures as more than a "blank slate" and standing building stock as more than mere three-dimensional structures ready to be built, changed, or demolished as a means to engineering and architectural ends. In fact, land and structures are human enterprises that affect people's lives directly. The Pruitt-Igoe public housing project in St. Louis, Missouri is a tragic and telling example of an engineering failure by one of the great contemporary architects that resulted from a lack of insights into the sense of place.

Thus, "failure" in design can go beyond textbook cases and those shared by our mentors and passed on from our predecessors. By most accounts, Minoru Yamasaki, was a highly successful designer and a prominent figure in the modernist architectural movement of the mid-twentieth century. Tragically and ironically, Yamasaki may best be remembered for two of his projects that failed. Yamasaki and Antonio Brittiochi designed the World Trade Center towers that were to become emblems of Western capitalism. Certainly, Yamasaki cannot be blamed, but the towers failed. In fact, the failure of architects for buildings is seldom structural and often aesthetic or operational (e.g., ugly or an inefficient flow of people). Yamasaki strived to present an aesthetically pleasing structure. One may argue that his architectural success in creating a structure so representative of contemporary America was a factor in its failure, making it a prime target of terrorists.

Most postcollapse assessments have agreed that the structural integrity of the towers was sufficient well beyond the expected contingencies. However, if engineers do not learn the lessons from this tragedy, they can rightfully be blamed. And the failure will be less a failure of applying of physical sciences (withstanding unforeseen stresses and strains) than a failure of imagination. Engineers have been trained to use imagination to envision a better way. Unfortunately, now we must imagine things that were unthinkable before September 11, 2001. Success depends on engaging the social sciences in our planning, design, construction, and maintenance of our projects. This will help to inform us of contingencies not apparent when applying the physical and natural sciences exclusively.

The Pruitt-Igoe housing development was a very different type of failure. The buildings, like the Manhattan towers, were another modernist monument. Rather than a monument to capitalism, Pruit Igoe was supposed to be emblematic of advances in fair housing and progress in the war on poverty. Regrettably, the development was to become an icon of failure of imagination, especially insights into the land ethic.

The Pruitt-Igoe fiasco occured at a time when the environmental ethos was changing. The land ethic was both the cause and the effect of this new thinking. Contemporary understanding of environmental quality is often associated with physical, chemical, and biological contaminants, but in the formative years of the environmental movement, aesthetics and other "quality of life" considerations were essential parts of environmental quality. Most environmental impact statements addressed cultural and social factors in determining whether a federal project would have a significant effect on the environment. These included historic preservation, economics, psychology (e.g., open space, green areas, crowding), aesthetics, urban renewal, and the *land ethic* as expressed by Aldo Leopold: "A thing is right when it tends to preserve the integrity, stability and beauty of the biotic community. It is wrong when it tends otherwise."[10]

The problems that led to the premature demolition of this costly housing experiment may have been anticipated intuitively if the designers had taken the time to understand what people expected. There is plenty of culpability to go around. Some blame the inability of the modern architectural style to create livable environments for people living in poverty, largely because they "are not the nuanced and sophisticated 'readers' of architectural space the educated architects were."[11] This is a telling observation and an important lesson for green designers. We need to make sure that the use and operation of whatever is designed is understood sufficiently well by those living with in and around it.

This transcends buildings and includes every design target (e.g. devices and landscapes). Other sources of failure have been suggested. Design incompatibility was almost inevitable for high-rise buildings and families with children. However, most large cities have large populations of families with children living in such environments. In fact, St. Louis had successful luxury townhomes not too far from Pruitt-Igoe. Another identified culprit was the generalized discrimination and segregation of the era. Actually, when inhabited originally, the Pruitt section was for blacks and Igoe was for whites.

Costs always become a factor. The building contractors' bids were increased to a level where the project construction costs in St. Louis exceeded the national average by 60%. The response to the local housing authority's refusal to raise unit cost ceilings to accommodate the elevated bids was to reduce room sizes, eliminate amenities, and raise densities.[12] As originally designed, the buildings were to become "vertical neighborhoods" with nearby playgrounds, open-air hallways, porches, laundries, and storage areas. The compromises eliminated these features; and the removal of some of the amenities led to dangerous situations. Elevators were undersized and stopped only every third floor and lighting was inadequate in the stairwells. So another lesson must be to know the difference between desirable and essential design elements. No self-respecting structural engineer involved in the building design would have shortcut the factors of safety built into load bearing. Conversely, human elements essential to a vibrant community were eliminated without much, if any, accommodation.[13]

Finally, the project was mismatched to the people who would live there. Many came from single-family residences. They were moved to a very large, imposing project with 2800 units and almost 11,000 people living there. This was quadruple the size of the next-largest project of the time.

When the failure of the project became overwhelmingly clear, the only reasonable decision was to demolish it, and this spectacular implosion became a lesson in failure for planners, architects, and engineers. In Yamasaki's own words, "I never thought people were that destructive. As an architect, I doubt if I would think about it now. I suppose we should have quit the job. It's a job I wish I hadn't done."[14]

Engineering is not only applied natural sciences; many engineers, especially when they advance to leadership positions in engineering, find themselves in professional situations in which the social sciences, including ethics, would be the set of skills that would be more valuable in determining their success as engineers. Teaching our students first to recognize and then to think through social problems is crucial to green design. We often overlook "teachable moments." For example, we repeatedly miss opportunities to relate engineering and social science lessons from even the most life- and society-changing events, such as the fall of the World Trade Center towers.[15]

The next stage of green engineering will require new thought processes. Thinking of engineering and architecture as "applied social science" redefines engineering and architecture from professions that build things to professions that help people. The extension of this conclusion should encourage educators to reevaluate what it is we teach our engineering students. We believe that all engineers and architects should include in their educational quiver at least some arrows that will help them make the difficult yet sustainable decisions faced by all design professionals.

This means that design professionals are risk reduction agents, if you will. Environmental challenges force designers to consider the physicochemical characteristics of the pollutants and match these with the biogeochemical characteristics of the media where these pollutants are found. We have had to increase our understanding of myriad ways that these characteristics would influence the time that these chemicals would remain in the environment, their likelihood to be accumulated in the food chain, and how toxic they would be to humans and other organisms. Those contaminants that have all three of these characteristics worry us the most. In fact, such contaminants have come to be known as "PBTs": persistent, bioaccumulating toxicants.

The problems at Love Canal, Times Beach, Valley of the Drums, and the many hazardous waste sites that followed them pushed regulators to approach pollutants from the perspective of risk. The principal value added by environmental professionals is the skill to improve the quality of human health and ecosystems. Thus, the change in risk is one of the best ways to measure the success of green designs. By extension, reliability lets us know how well we are preventing pollution, reducing exposures to pollutants, protecting ecosystems, and even protecting the public welfare (e.g., buildings exposed to low-pH precipitation).

Risk, as it is generally understood, is the chance that some unwelcome event will occur. The operation of an automobile, for example, introduces the driver and passengers to the risk of a crash that can cause damage, injuries, and even death. Environmental failures have emphasized the need to somehow quantify and manage risks. Understanding the factors that lead to a risk is known as *risk analysis.* The reduction of this risk (e.g., by wearing seat belts in the driving example) is *risk management.* Risk management is often differentiated from *risk assessment*, which is comprised of the scientific considerations of a risk. Risk management includes the policies, laws, and other societal aspects of risk.

Designers must consider the interrelationships among factors that put people at risk, suggesting that we are risk analysts. As mentioned, green designs must be based on sound application of the physical sciences. Sound science must be the foundation of risk assessments. Engineers control things and, as such, are risk managers. Engineers are held responsible for designing safe products and processes, and the public holds us accountable for its health, safety, and welfare. Similarly, architects must provide designs that are sustained in the best interests of their clients. The public expects designers to "give results, not excuses,"[16] and risk and reliability are accountability measures of their success. Engineers design systems to reduce risk and look for ways to enhance the reliability of these systems. Thus, green design deals directly or indirectly with risk and reliability.

Both risk and reliability are probabilities. People living in or near what we design, at least intuitively, assess the risks, and when presented solutions by technical experts, make decisions about the reliability of the designs. They, for good reason, want to be assured that they will be "safe." But *safety* is a relative term. Calling something safe integrates a value judgment that is invariably accompanied by uncertainties. The safety of a building, product or process can be described in objective and quantitative terms. Factors of safety are a part of every design.

Success or failure as designers is in large measure determined by what we do compared to what our profession "expects" us to do. Safety is a fundamental facet of our duties. Thus, we need a set of criteria that tells us when designs and projects are sufficiently safe. Four safety criteria are applied to test engineering safety[17]:

1. The design must comply with applicable laws.
2. The design must adhere to "acceptable engineering practice."
3. Alternative designs must be sought to see if there are safer practices.
4. Possible misuse of a product or process must be foreseen.

These four provisions are the starting point for sustainable design.

Sustainability

Their recognition of an impending and assured global disaster led the World Commission on Environment and Development, sponsored by the United Nations, to conduct a study of the world's resources. Also known as the Brundtland Commission, their 1987 report *Our Common Future* introduced the term *sustainable development* and defined it as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs."[18] The United Nations Conference on Environment and Development (UNCED), that is, the Earth Summit held in Rio de Janeiro in 1992, communicated the idea that sustainable development is both a scientific concept and a philosophical ideal. The document, *Agenda 21*, was endorsed by 178 governments (not including the United States) and hailed as a blueprint for sustainable development. In 2002, the World Summit on Sustainable Development identified five major areas that are considered essential in moving sustainable development plans forward.

The underlying purpose of sustainable development is to help developing nations manage their resources, such as rain forests, without depleting these resources and making them unusable for future generations. In short, the objective

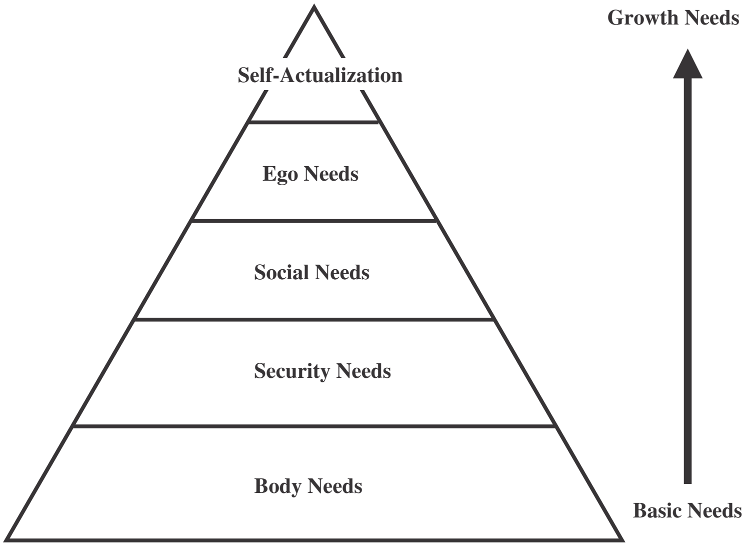


Figure 4.6 Maslow's hierarchy of needs. The lower part of the hierarchy (i.e., basic needs) must be satisfied before a person can advance to the next growth levels.

is to prevent the collapse of global ecosystems. The Brundtland report presumes that we have a core ethic of intergenerational equity and that future generations should have an equal opportunity to achieve a high quality of life. The goal is a sustainable global ecologic and economic system, achieved in part by the wise use of available resources.

We are creatures that have different needs. Psychologist Abraham Maslow[19] articulated this as a hierarchy of needs consisting of two classes of needs: basic and growth (see Fig. 4.6). The basic needs must be satisfied before a person can progress toward higher-level growth needs. Within the basic needs classification, Maslow separated the most basic physiological needs, such as water, food, and oxygen, from the need for safety. Therefore, one must first avoid starvation and thirst, satisfying minimum caloric and water intake, before being concerned about the quality of the air, food, and water. The latter is the province of environmental protection. The most basic of needs must be satisfied before we can strive for more advanced needs. Thus, we need to ensure adequate quantities and certain ranges of quality of air, water, and food. Providing food requires ranges of soil and water quality for agriculture. Thus, any person and any culture that is unable to satisfy these most basic needs cannot be expected to "advance" toward higher-order values such as free markets and peaceful societies. In fact, the inability to provide basic needs militates against peace. This means that when basic needs go unmet, societies are frustrated even if they strive toward freedom and peace; and even those that begin may enter into vicious cycles wherein any progress is undone by episodes of scarcity. We generally think of peace and justice as the province of religion and theology, but green engineers and architects will increasingly be called upon to "build a better world."

Even mechanical engineers, whom we may at first blush think of as being concerned mainly about nonliving things, are embracing *sustainable design* in a large way. In fact, in many ways the mechanical engineering profession is out in front on sustainable design. For example, the ASME Web site draws a systematic example from ecology: "To an engineer, a sustainable system is one that is in equilibrium or changing at a tolerably slow rate. In the food chain, for example, plants are fed by sunlight, moisture and nutrients, and then become food themselves for insects and herbivores, which in turn act as food for larger animals. The waste from these animals replenishes the soil, which nourishes plants, and the cycle begins again."[20]

Sustainability is, therefore, a systematic phenomenon, so it is not surprising that engineers have embraced the concept of sustainable design. At the largest scale, manufacturing, transportation, commerce, and other human activities that promote high consumption and wastefulness of finite resources cannot be sustained. At the individual designer scale, the buildings, products and processes that engineers design must be considered for their entire useful lifetimes and beyond.

The Tragedy of the Commons

Since sustainability requires knowing what is important, it requires a sense of what is valued by the client, who is ultimately the public. In addition, such thinking requires some forecast of what will be valued in the future, which means that we need a way to divvy up the values among the disparate groups that comprise the present and future stakeholders. Garrett Hardin (1915–2003) postulated a means of doing this. Hardin was a biologist by training and an ethicist by reputation. In 1968 he wrote a hugely influential article entitled "The Tragedy of the Commons," which has become a "must-read" in every ecology course and increasingly in ethics courses. In this article Hardin imagines an English village with a common area where everyone's cow may graze. The common is able to sustain the cows, and village life is stable until one of the villagers figures out that if he gets two cows instead of one, the cost of the extra cow will be shared by everyone while the profit will be his alone. So he gets two cows and prospers, but others see this and similarly want two cows. If two, why not three—and so on—until the village common is no longer able to support the large number of cows, and everyone suffers.[21]

A similar argument can be made for the use of nonrenewable resources. If we treat diminishing resources such as oil and minerals as capital gains, we will soon find ourselves in the "common" difficulty of having an insufficient support system.

Hardin's parable, however, does demonstrate that even though the individual sees the utility of preservation (no new cows) in a collective sense, the ethical egoistic view may well push the decision toward immediate gratification of the individual at the expense of the collective good. Tragically, this view can result in large-scale harm (e.g., artifacts of pollution, waste of resources, legacies of diseases, exhaustion of resources).

Ethics of Place

Let us venture more deeply into the realm of ethics. After all, ethics is intricately tied to sustainability. Ultimately, ethics tells us what we *ought to do.* It informs us of how we need to think about ourselves and others. These others can be near or distant, present or future. If we seek sustainable designs, all of these must be served. Thus, as mentioned, ethics has dimensions in space and time.

Green design is a virtuous endeavor. *Virtue ethics* is the ethical theory that emphasizes the virtues, or moral character, in ethical decision making. It focuses on what makes a good person rather than what makes a good action. People who devote their lives to doing the right thing are said to behave virtuously. Aristotle tried to clarify the dichotomy of good and evil by devising lists of virtues and vices which amount to a taxonomy of good and evil. One of the many achievements of Aristotle was his keen insight as to the similarities of various kinds of living things. He categorized organisms into two kingdoms, plants and animals. Others no doubt made such observations, but Aristotle documented them. He formalized and systematized this taxonomy. Such a taxonomic perspective also found its way into Aristotle's moral philosophy.

The classical works of Aristotle, Thomas Aquinas, and others make the case for life being a mix of virtues and vices available to humans. *Virtue* can be defined as the power to do good or a habit of doing good. In fact, one of Aristotle's most memorable lines is that "Excellence is habit." If we do good, we are more likely, according to Aristotle, to keep doing good. Conversely, *vice* is the power and habit of doing evil. The subjectivity or relational nature of good and evil, however, causes discomfort among engineers. We place great import on certainty and consistency of definition.

We all will not all agree on which of the virtues and vices are best or even whether something is a virtue or a vice (e.g., loyalty), but one concept does seem to come to the fore in most major religions and moral philosophies: empathy. Putting oneself in another's situation is a good metric for virtuous acts.

Green design also has a beneficial end in mind. *Consequentialism* holds that the value of an action derives solely from the value of its consequences. Consequentialists believe that the consequences of a particular action form the basis for any valid moral judgment about that action, so that a morally right action is an action that produces good consequences. One type of consequentialism is that of utilitarianism, which measures the ethical value in terms of greatest good for the greatest number. "The Tragedy of the Commons" points to the problem of consequentialism and utilitarianism in the absence of sustainability. That is, if people view values exclusively in terms of their present and personal needs, collective costs will be incurred. For example, if energy needs of this generation is the sole target of the "greatest good," future generations may be left with enormous costs (e.g., global climate change, loss of habitat, exposure to persistent pollutants).

Green design is our obligation to society. This is *deontology*, or duty-based ethics. Immanuel Kant is recognized as the principal advocate of this school of thought. Duty can be summed up as the categorical imperative. To paraphrase Kant, the *categorical imperative* states that when deciding whether to act in a certain way, you should ask yourself if your action (or inaction) will make for a better world if all others in your situation acted in the same way. In other words, should your action be universalized? If so, it is your duty to take that action. If not, it is your duty to avoid that action.

This requires that for a design to meet these ethical requirements, its potential good and bad outcomes must be viewed cumulatively. A single action or step in the design process is less important than the comprehensive result of each action or step. Thus, the life cycle dictates whether the action is right or wrong, at least from a design standpoint. The benefits and risks to the environment may cause one to rethink a process in the life cycle. Thus, the life cycle illustrates what we might call the "green categorical imperative". We may very much like one of our steps (e.g., a large building lot that provides a vista), but if it leads to negative consequences (e.g., housing that is not affordable), these may outweigh the single-minded benefits.

Green design is not the exclusive domain of duty ethics. In consequentialism, the life-cycle viewpoint is one of the palliative approaches to dealing with the problem of "ends justifying the means." In fact, John Stuart Mill's utilitarianism's axiom of "greatest good for the greatest number of people" is moderated by his *harm principle*, which, at its heart takes into account the potential impact of an action on others now and in the future. That is, even though an act can be good for the majority, it may still be unethical if it causes undue harm to even one person.

The life cycle also comes into play in *contractarianism*, as articulated by Thomas Hobbes as social contract theory. For example, John Rawls has moderated the social contract with the "veil of ignorance" as a way to consider the perspective of the weakest, one might say "most disenfranchised," members of society. Finally, the rational-relationship ethical frameworks incorporate empathy into all ethical decisions when they ask the guiding question: What is going on here? In other words, what benefit or harm, based on reason, can I expect from actions brought about by the decision I am about to make? One calculus of this harm or benefit is to be empathetic to all others, particularly the weakest members of society, those with little or no "voice." Thus, the design professional must keep these members of society in mind despite the loud voices of politicians, investors, and others who would dictate less than green design decisions.

Implementing Sustainable Designs

Sustainability requires adopting new and better means of using materials and energy. The operationalizing of the quest for sustainability is defined as *green engineering,* a term that recognizes that engineers are central to the practical application of the principles of sustainability to everyday life. The relationship between sustainable development, sustainability, and green engineering is progressive:

$$\begin{bmatrix}\text{sustainable}\\ \text{development}\end{bmatrix} \rightarrow \begin{bmatrix}\text{green architecture}\\ \text{and engineering}\end{bmatrix} \rightarrow \begin{bmatrix}\text{sustainability}\end{bmatrix} \rightarrow \begin{bmatrix}\text{sustainable}\\ \text{design}\end{bmatrix}$$

Sustainable development is an ideal that can lead to sustainability, but this can only be done through green engineering.

Green architecture and engineering[22] treat environmental quality as an end in itself. The EPA amplifies the importance of the interrelationships of feasibility, environmental quality, public health, and welfare:

> the design, commercialization, and use of processes and products, which are feasible and economical while minimizing 1) generation of pollution at the source and 2) risk to human health and the environment. The discipline embraces the concept that decisions to protect human health and the environment can have the greatest impact and cost effectiveness when applied early to the design and development phase of a process or product.[23]

Green engineering approaches are continuously being integrated into engineering guidelines. This is made easier with improved computational abilities (see Table 4.3) and other tools that were not available at the outset of the environmental movement. Increasingly, companies have come to recognize that improved efficiencies save time, money, and other resources in the long run. Hence, companies are thinking systematically about the entire product stream in numerous ways:

- Applying sustainable development concepts, including the framework and foundations of "green" design and engineering models
- Applying the design process within the context of a sustainable framework, including considerations of commercial and institutional influences

Table 4.3 Principles of Green Programs

Principle	Description	Example	Computational and Other Engineering Tools
Waste prevention	Design chemical syntheses and select processes to prevent waste, leaving no waste to treat or clean up.	Use a water-based process instead of an organic solvent–based process.	Bioinformatics and data mining can provide candidate syntheses and processes.
Safe design	Design products to be fully effective, yet have little or no toxicity.	Use microstructures, instead of toxic pigments, to give color to products. Microstructures bend, reflect, and absorb light in ways that allow for a full range of colors.	Systems biology and "omics" technologies (i.e., genomics, proteomics, metabanonics) can support predictions of cumulative risk from products used in various scenarios.
Low-hazard chemical synthesis	Design syntheses to use and generate substances with little or no toxicity to humans and the environment.	Select chemical synthesis with toxicity of the reagents in mind upfront. If a reagent ordinarily required in the synthesis is acutely or chronically toxic, find another reagent or new reaction with less toxic reagents.	Computational chemistry can help predict unintended product formation and reaction rates of optional reactions.
Renewable material use	Use raw materials and feedstocks that are renewable rather than those that deplete nonrenewable natural resources. Renewable feedstocks are often made from agricultural products or are the wastes of other processes; depleting feedstocks are made from fossil fuels (petroleum, natural gas, or coal) or that must be extracted by mining.	Construction materials can be from renewable and depleting sources. Linoleum flooring, for example, is highly durable, can be maintained with non-toxic cleaning products, and is manufactured from renewable resources amenable to being recycled. Upon demolition or re-flooring, the linoleum can be composted.	Systems biology, informatics, and "omics" technologies can provide insights into the possible chemical reactions and toxicity of the compounds produced when switching from depleting to renewable materials.
Catalysis	Minimize waste by using catalytic reactions. Catalysts are used in small amounts and can carry out a single reaction many times. They are preferable to stoichiometric reagents, which are used in excess and work only once.	The Brookhaven National Laboratory recently reported that it has found a "green catalyst" that works by removing one stage of the reaction, eliminating the need to use solvents in the process by which many organic compounds are synthesized. The catalyst dissolves into the reactants. Also, the catalyst has the unique ability of being easily removed and recycled because, at the end of the reaction, the catalyst precipitates out of products as a solid material, allowing it to be separated from the products without using additional chemical solvents.[a]	Computation chemistry can help to compare rates of chemical reactions using various catalysts. Quantitative structural activity relationships can help to predict possible adverse effects of chemicals before they are manufactured.

Table 4.3 Principles of Green Programs (*Continued*)

Principle	Description	Example	Computational and Other Engineering Tools
Avoiding chemical derivatives	Avoid using blocking or protecting groups or any temporary modifications if possible. Derivatives use additional reagents and generate waste.	Derivativization is a common analytical method in environmental chemistry (i.e., forming new compounds that can be detected by chromatography). However, chemists must be aware of possible toxic compounds formed, including leftover reagents that are inherently dangerous.	Computational methods and natural products chemistry can help scientists start with a better synthetic framework.
Atom economy	Design syntheses so that the final product contains the maximum proportion of the starting materials. There should be few, if any, wasted atoms.	Single atomic- and molecular-scale logic used to develop electronic devices that incorporate design for disassembly, design for recycling, and design for safe and environmentally optimized use.	The same amount of value (e.g., information storage and application) is available on a much smaller scale. Thus, devices are smarter and smaller, and more economical in the long term. Computational toxicology enhances the ability to make product decisions with better predictions of possible adverse effects, based on logic.
Nanomaterials	Tailor-make materials and processes for specific designs and intent at the nanometer scale ($\leq$ 100 nm).	Provide emissions, effluent, and other environmental controls; design for extremely long life cycles. Limits and provides better control of production and avoids overproduction (i.e., a "throwaway economy").	Use improved, systematic catalysis in emission reductions (e.g., large sources like power plants and small sources like automobile exhaust systems). Zeolite and other sorbing materials used in hazardous waste and emergency response situations can be better designed by taking advantage of surface effects; this decreases the volume of material used.
Selection of safer solvents and reaction conditions	Avoid using solvents, separation agents, or other auxiliary chemicals. If these chemicals are necessary, use innocuous chemicals.	Supercritical chemistry and physics, especially that of carbon dioxide and other safer alternatives to halogenated solvents are finding their way into the more mainstream processes, most notably dry cleaning.	To date, most of the progress as been the result of wet chemistry and bench research. Computational methods will streamline the process, including quicker scale-up.
Improved energy efficiencies	Run chemical reactions and other processes at ambient temperature and pressure whenever possible.	To date, chemical engineering and other reactor-based systems have relied on "cheap" fuels and, thus have optimized on the basis of thermodynamics. Other factors (e.g., pressure, catalysis, photovoltaics, fusion) should also be emphasized in reactor optimization protocols.	Heat will always be important in reactions, but computational methods can help with relative economies of scale. Computational models can test the feasibility of new energy-efficient systems, including intrinsic and extrinsic hazards (e.g., to test certain scale-ups of hydrogen and other economies). Energy behaviors are scale-dependent. For example, recent measurements of H_2SO_4 bubbles when reacting with water have temperatures in range of those found the surface of the sun.[b]

(*Continued*)

Table 4.3 Principles of Green Programs (*Continued*)

Principle	Description	Example	Computational and Other Engineering Tools
Design for degradation	Design chemical products to break down to innocuous substances after use so that they do not accumulate in the environment.	Biopolymers (e.g., starch-based polymers) can replace styrene and other halogen-based polymers in many uses. Geopolymers (e.g., silane-based polymers) can provide inorganic alternatives to organic polymers in pigments, paints, etc. These substances, when returned to the environment, become their original parent form.	Computation approaches can simulate the degradation of substances as they enter various components of the environment. Computational science can be used to calculate the interplanar spaces within the polymer framework. This will help to predict persistence and to build environmentally friendly products (e.g., those where space is adequate for microbes to fit and biodegrade the substances).
Real-time analysis to prevent pollution and concurrent engineering	Include in-process real-time monitoring and control during syntheses to minimize or eliminate the formation of by-products.	Remote sensing and satellite techniques can provide be linked to real-time data repositories to determine problems. The application to terrorism using nanoscale sensors is promising.	Real-time environmental mass spectrometry can be used to analyze whole products, obviating the need for any further sample preparation and analytical steps. Transgenic species, although controversial, can also serve as biological sentries (e.g., fish that change colors in the presence of toxic substances).
Accident prevention	Design processes using chemicals and their forms (solid, liquid, or gas) to minimize the potential for chemical accidents, including explosions, fires, and releases to the environment.	Scenarios that increase probability of accidents can be tested.	Rather than waiting for an accident to occur and conducting failure analyses, computational methods can be applied in prospective and predictive mode; that is, the conditions conducive to an accident can be characterized computationally.

Source: First two columns, except "Nano-materials," adapted from U.S. Environmental Protection Agency, "Green chemistry," http://www.epa.gov/greenchemistry/principles.html, 2005, accessed April 12, 2005. Other information from discussions with Michael Hays, U.S. EPA, National Risk Management Research Laboratory, April 28, 2005.

[a] U.S. Department of Energy, Research News, http://www.eurekalert.org/features/doe/2004-05/dnl-brc050604.php, accessed March 22, 2005.

[b] D. J. Flannigan and K. S. Suslick. "Plasma formation and temperature measurement during single-bubble cavitation," *Nature*, 434, 52–55, 2005.

- Considering practical problems and solutions from a comprehensive standpoint to achieve sustainable products and processes
- Characterizing waste streams resulting from designs
- Understanding how first principles of science, including thermodynamics, must be integral to sustainable designs in terms of mass and energy relationships, including reactors, heat exchangers, and separation processes
- Applying creativity and originality in group product and building design projects

As discussed in Chapter 3, numerous industrial, commercial, and governmental green initiatives are under way: notably design for the environment, design for disassembly, and design for recycling.[24] These are replacing or at least changing pollution control paradigms. The call for improved design approaches is leading not only to fewer toxics leaving pipes, vents, and stacks, but also to improvements to the financial bottom line. Most sustainable design approaches, such as life-cycle analysis, prioritizing the most important problems, and matching the technologies and operations to address them, are a means to improving efficiencies. But green thinking goes well beyond improved efficiencies. In fact, finding more effective means of carrying out a function is a better view.

Examples of changing focus from prototypes to function are abundant. Let us consider the burgeoning area of entertainment. A couple of decades ago, if you wanted to be entertained by seeing a movie, you had two choices. You could see a new movie in a theater or you could wait a few years and see the same movie, in edited form, on your television set. Next, video players were made widely available, so a new option emerged. You could go to the video store and rent a recent (but not new) movie and watch it in the privacy of your home. Although this was a new means of viewing the video, it was really not a change in function but a modification of an existing design. In fact, most ways to see a movie—that is, the function of motion picture watching—have not changed. We saw improvements in presentation (e.g., improved sound systems, high-definition technologies, and recording capabilities), but not in the function itself.

This is an example of keeping the prototype but not substantially changing the function. To change the function, we have to rethink the entire concept of motion picture entertainment. For example, the same function can be improved by choosing Earth-friendly materials in building the theater, improving its HVAC system to be more energy efficient, even using media with fewer toxics (e.g., eliminating silver-based films). However, a truly new function might be to eliminate the need to drive to the theater in the first place. If we can find a way to bring the movie to the individual viewer in just as good a quality as in the theater, we have changed the function not merely the presentation. Some of the emerging entertainment technologies are approaching this, such as I-Pod and other players.

With the change in function, there are often unintended consequences. For instance, would we exacerbate the desocializing or even antisocial behaviors that have accompanied video games and private entertainment systems? Are there unexpected risks? Too often, breakthroughs are met with uneven risks to certain members of society, such as children, minority groups, and compromised subpopulations. This is not meant to discourage innovation, only to consider all possible outcomes.

Historically, environmental considerations have been approached by engineers as constraints on their designs. For example, hazardous substances generated by a manufacturing process were dealt with as a waste stream that must be contained and treated. The hazardous waste production had to be constrained by selecting certain manufacturing types, increasing waste-handling facilities, and if these did not entirely do the job, limiting rates of production. Green engineering emphasizes the fact that these processes are often inefficient economically and environmentally, calling for a comprehensive, systematic life-cycle approach. Green engineering attempts to achieve four goals:

1. Waste reduction
2. Materials management
3. Pollution prevention
4. Product enhancement

WHAT'S NEXT?

Green design requires sorting through what is hype and what is truly a technological breakthrough. This can be likened to a physician who is inundated daily with literature from the pharmaceutical industry on all the new drugs that will allow her to be a more effective doctor, the seemingly endless series of visits from pharmaceutical reps, and the sharing of success stories with colleagues in person or virtually on Web sites. How does one separate the wheat from the chaff? The green designer is confronted with similar ill-posed problems. What is the best software for hazardous waste design? How different, really, is the new genetically altered species from those grown from native soils? What is the value added of an early warning system for a drinking water plant? What are the added risks of intervention versus letting nature take its course (i.e., "natural attenuation")?

The Future Engineer (FE), Professional Engineer (PE), and American Institute of Architects (AIA) certification processes will become even more important. The time while the emerging engineer is learning the ins and outs of the profession from seasoned professionals will increase in importance. And perhaps even more important, the new engineer will need a whole host of mentors beyond the PE and AIA. We have talked about the interdisciplinary nature of green design. Thus, each discipline and perspective calls for a mentor. The actual amount of tutelage will vary considerably. If a designer seeks to design and oversee wetland restoration projects, hands-on experience with wetland ecologists is vital. If the designer is more concerned about hazardous waste remediation, some time in the laboratory of an environmental analytical chemist would be worthwhile. In both cases, after the initial experience, career-long relationships with these mentors should be maintained. The green designer has tools that were not available to earlier generations of designers. E-mail and file sharing allow for ongoing relationships and real-time advice. This is particularly important when confronted with a complex or new problem. The mix of inputs from trusted mentors could make for a solution very different from one where only handbooks are consulted. For example, most professors are gratified when a former student or employee contacts them about a specific problem or project. The mentor often has to go back to his or her files or spend some time remembering similar situations, but enjoys the challenge. This mentor–learner model also helps to ensure that the knowledge and wisdom of this generation are passed on to the next (i.e., providing a way to preserve "corporate" memory in the ever-changing fields of green design).

The sheer amount and complexity of data and information is enormous at present and will continue to grow. In environmental engineering we have always had to make decisions in the face of great amounts of uncertainty. Generally, uncertainty comes from many sources. The data available to designers always include some variability. The instruments used to gather the data will always have internal variability (e.g., drift or effects from concentrations of chemicals being tested). They will also have external variability, such as operator variability and temperature and pressure differences. Detection limits for chemicals, for example, will vary from lab to lab and instrument to instrument. This results from differences in standards, reagents, operators, instrument components (e.g., wattage in lamps, types of mass spectrometry), and the standard operating procedures at various labs. What we test is also highly variable. Air, water, sediment, soil, and biota are dynamic systems. The water content in each varies temporally. Sediment and soil organic contents vary slightly in the near term (e.g., hours), but sometimes significantly over the long term (e.g., seasons, years).

The measurements that we take are often not quite as "direct" as we may like to think. And even if data are straightforward to those of us who are technically savvy, a lot of what scientists and engineers do does not always seem logical to a broader audience. Thus, explaining the meaning of data can be very challenging. That is due, in part, to the incompleteness of our understanding of the methods used to gather data. Even well-established techniques such as chromatography have built-in uncertainties. Since accuracy is how close we are to the "true value" or reality, our instruments and other methods only provide data, not information, and certainly not knowledge and wisdom. In chromatography, for example, we are fairly certain that the peaks we are seeing represent the molecule in question, but actually, depending on the detector, all we are seeing is the number of carbon atoms (e.g., flame ionization detection) or the mass/charge ratios of molecular fragments (e.g., mass spectrometry), not the molecule itself. Add to this, instrument and operator uncertainties and one can see that even the more accepted scientific approaches are biased and inaccurate, let alone approaches such as mathematical modeling, where assumptions about initial and boundary conditions, values given to parameters, and the propagation of error render our results even more uncertain.

Thus, professional judgment is crucial to sound design. Such judgment can only come from learning from the experiences of those who precede us and from our own experiences. It is a challenge to find the sweet spot between acceptable and unacceptable risk, but that is the only place where good and green design can be found.

NOTES AND REFERENCES

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2. U.S. Environmental Protection Agency, "Green engineering", http://www.epa.gov/oppt/greenengineering/, 2006, accessed June 13, 2006.
3. Virginia Polytechnic Institute and State University, http://www.eng.vt.edu/green/Program.php, 2006, accessed June 13, 2006.
4. This definition comes from the Worcester Polytechnic Institute, http://www.wpi.edu/Academics/Depts/CHE/About/definition.html.
5. I (Vallero) first heard Vesilind publicly share this profundity during an engineering conference. At first blush, the statement sounds like a truism, or even silly, unless one thinks about it. There are many, and a growing number of, enterprises that do not *do* anything (or at least it is difficult to tell what they do). They think about things, they come up with policies, they review and critique the work of others, but their value added is not so "physical." I have to say that I envy my family members and friends in construction who at the end of every working day see a difference because of what they did that day. This can take many forms, such as a few more meters of roadway, a new roof, or an open lot where a condemned structure once stood. The great thing about green engineering is that we can do both. We can plan and do. I should say we *must both plan and do!* In the words of the woodworker, we must "measure twice and cut once." The good news (and the responsibility) is that the green engineer's job is not finished when the blueprints are printed. The job is not even over when the project is built. The job continues for the useful life of the project. And since most environmental projects have no defined end but are in operation continuously, the engineers get to watch the outcomes indefinitely. Engineers must get out there and observe (and oversee) the fulfillment of their ideas and the implementation of their plans. That is why engineers are called to "do things."

   This reminds me of a conversation I had with a boilermaker who happens to be my in-law, which points out that engineers need to be aware of the knowledge and wisdom all around them (not just from texts, manuals, or even old professors). He has been installing, welding, and rigging huge boiler systems for power plants and refineries for decades and has a reputation among his fellow boilermakers as being both highly intelligent and highly skilled at his craft. He recently shared with me that he likes to work with "young engineers," mainly because they listen. They are not concerned about hierarchies or "chain of command" so much as some of the more senior engineers or managers. Perhaps it is because they know so little about the inner workings of complex and large systems like those needed in coal-fired combustion. They also seem to know how to have fun. He contrasts this with the engineer who shows up on the job and lets everyone know that he is the "pro." My in-law recounts one memorable occasion when one such arrogant professional chose not to or did not know to ask the boilermakers about what happens when a multiton boiler tank is rigged. Had he asked, the boilermaker would have shared the extent of his knowledge about "stretching." In other words, the height of the superstructure had to be sufficiently taller than the boiler to account for the steel alloy elasticity due to the tremendous weight. As it was designed, the superstructure was too short, so the boiler stretched all the way to the ground surface and the entire thing had to be redesigned and retrofitted. Had the professional asked, he would have known early on to modify the design. My in-law surmises that the "young guys" would have asked. My guess is that, out of respect, even if they hadn't asked, he would have warned them simply because they put him in a place where he could communicate with them. The moral of this story is that leadership often comes from places other than the top. Another moral is: As you mature, don't forget what made you successful in the first place.

6. T. S. Kuhn, *The Structure of Scientific Revolutions*, University of Chicago Press, Chicago, 1962. Kuhn actually changed the meaning of the word *paradigm*, which had been almost the exclusive province of grammar (a fable or parable). Kuhn extended the term to mean an accepted specific set of scientific practices. The scientific paradigm is made up of what is to be observed and analyzed, the questions that arise pertaining to this scientific subject matter, to whom such questions are to be asked, and how the results of the investigations into this subject matter will be interpreted. The paradigm can be harmful if it allows incorrect theories and information to be accepted by the scientific and engineering communities. Such erroneous adherences can result from *groupthink*, a term coined by Irving Janis, a University of California–Berkeley psychologist. Groupthink is a collective set of systematic errors (biases) held by and perpetuated by a group. See I. Janis, *Groupthink: Psychological Studies of Policy Decisions and Fiascoes*, 2nd ed., Houghton Mifflin, Boston, MA, 1982.
7. R. Ludlow, "Green architecture," Environmental Studies 399 Senior Capstone, St. Olaf College, Northfield, MN, http://www.stolaf.edu/

depts/environmental-studies/courses/es-399%20home/es-399-04/Projects /Ludlow_Project/place.html, accessed August 5, 2007. Cited within this quote: J. Kennedy, Ed., *Natural Buildings: Design, Construction, Resources*, New Society Publishers, Vancouver, Canada, 2002.

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16. C. Mitcham and R. S. Duval, "Responsibility in engineering", Chapter 8 in *Engineering Ethics*, Prentice Hall, Upper Saddle River, NJ, 2000.
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18. United Nations, World Commission on Environment and Development, *Our Common Future,* Oxford Paperbacks, Oxford, 1987.
19. Abraham Maslow, *Motivation and Personality*, 2nd ed., Harper & Row, New York, 1970.
20. American Society of Mechanical Engineers, Professional Practice Curriculum: "Sustainability," http://www.professionalpractice.asme.org/ communications/sustainability/index.htm, 2004, accessed November 2, 2004.
21. A thread running all through Hardin's books is that ethics has to be based on rational argument and not on emotion. His most interesting book is *Stalking the Wild Taboo*, in which he takes on any number of social conceptions that demand rational reasoning. However, like many of those aggressively advocating scientism, his views approach rationalism so that only that which can be measured can be said to exist.

    This view, when taken to the extreme, can exclude human qualities such as happiness or the human soul. It can also lead to an extreme form of biocentrism or ecocentrocism, known as *deep ecology*. This is actually a modern form of *utilitarianism*, holding that nature and the natural order should be valued over individual human happiness, which has even spawned views that the worth of certain human beings (e.g., newborns, elderly, the infirm) is less than that of more sentient beings. Consider this quote by the ecocentrist Peter Singer: "In our book, *Should the Baby Live?,* my colleague Helga Kuhse and I suggested that a period of twenty-eight days after birth might be allowed before an infant is accepted as having the same right to life as others". (P. Singer, *Rethinking Life and Death*, St. Martin's Griffin, New York, 1996, p. 217.)

Such views are counter to the engineer's first canon, which is to hold paramount the safety, health, and welfare of the public. In fact, the socially responsible and green engineer has an ethical obligation to the most vulnerable members of society. Most of our plans cannot be targeted for the healthiest or strongest but for the most sensitive. For example, air pollution controls need to protect infants, the elderly, asthmatics, and others sensitive to airborne contaminants. Similarly, food and water supplies must meet standards to protect the more vulnerable members of society (e.g., those with allergies, young children). Thus, the life cycle extends beyond a single point in time and space.

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chapter 5

Sustainable Design and Social Responsibility

Green design encompasses numerous ways to improve processes and products to make them more efficient from an environmental standpoint. Every one of these approaches depends on viewing possible impacts in space and time and using assertive design approaches to prevent or ameliorate them. Thus, green design is teeming with opportunities to enhance our world.

Time of is of the essence. Green design requires a prospective view that anticipates artifacts. In fact, this is the essence of *design for disassembly* (DFD). One of the best counterexamples of DFD appeared in a magazine and in the 1970s, which showed a hand throwing out a disposable razor. The razor magically disappeared. In fact, it is likely that razor is still intact in a landfill somewhere. The life of the project continues well after the build phase, and even after the useful life of the building, device, or other design target. Thus, DFD is not simply keeping an eye for the use of materials, vacated land, or other remnants of the project. It is a view of utility beyond the use phase predicted. Certainly, this requires postuse considerations, such as insisting on the use of reusable materials and considerations of obsolescence of parts and the entire system. In addition, it requires thinking about uses after the first stage of usage and the avoidance ("down cycling"). For example, if a neighborhood demographic were to change in the next century, is the design sufficiently adaptive to continue to be useful for this new set of users? This is not so unusual, as in the case of well-planned landfills, which may have a few decades of waste storage, followed by many decades of park facilities. How many strip malls or shopping centers were designed for but a few decades of use, followed by abandonment and desolation of neighboring communities in their wake? It is the height of arrogance to assume that a development or building will not change with respect to its social milieu. Building design must embrace the idea of "long-life/loose fit" and be sufficiently flexible to accomodate a variety of adaptive reuse scenarios.

Engineering and architecture have always been concerned with space. Architects consider the sense of place. Engineers view the site map as a set of fluxes across the boundary. Time is a bit more difficult. The design must consider short- and long-term impacts. Sometimes these impacts will be on futures beyond ours.

The effects may not manifest themselves for decades. In the mid-twentieth century, designers specified the use of what are now known to be hazardous building materials, such as asbestos flooring, pipe wrap, and shingles, lead paint and pipes, and structural and mechanical systems that may have increased exposure to molds and radon. Those decisions have led to risks to people inhabiting these buildings. It is easy in retrospect to criticize these decisions, but many were made for noble reasons, such as fire prevention and durability of materials. However, it does illustrate that when viewed through the prism of time, seemingly small impacts can be amplified exponentially in their effects.

Sustainable design requires a complete assessment of a design in place and time. We mentioned that the effects can be decades away. In fact, they may be centuries or even millennia in the future. For example, the extent to which we decide to use nuclear power to generate electricity is a sustainable design decision. The radioactive wastes may have half-lives of hundreds of thousands of years. That is, it will take all these years for half of the radioactive isotopes to decay. Radioactive decay is the spontaneous transformation of one element into another. This occurs by irreversibly changing the number of protons in the nucleus. Thus, sustainable designs of such enterprises must consider highly uncertain futures. For example, even if we place warning signs about these hazardous wastes properly, we do not know if the English language will be understood.

All four goals of green engineering mentioned above are supported by a long-term life-cycle point of view. A life-cycle analysis is a holistic approach to considering the entirety of a product, process, or activity, encompassing raw materials, manufacturing, transportation, distribution, use, maintenance, recycling, and final disposal. In other words, assessing its *life cycle* should yield a complete picture of the product.

The first step in a life-cycle assessment is to gather data on the flow of a material through an identifiable society. Once the quantities of various components of such a flow are known, the important functions and impacts of each step in the production, manufacture, use, and recovery/disposal are estimated. Thus, in *sustainable design,* we must optimize for variables that give us the best performance in a temporal sense.

REVISITING THE HARM PRINCIPLE: MANAGING RISKS

The *harm principle* espoused by John Stuart Mill basically, tells us that even when benefits clearly outweigh costs, we are still morally obliged not to take such action if it causes undo harm to even a few people. This is a difficult concept for those who operate in the quantitative domain, as most engineers and architects do. The harm principle becomes even more complicated when not taking an action can lead to its own negative consequences. For example, consider a community with substandard housing with a number of abandoned structures in need of demolition. Further, some of these structures were constructed with asbestos-containing building materials. There are a number of critical paths that could be followed to address the need for better housing, but all of them involve some risk of harm to others. If we decide to demolish the structures, there is a potential for exposure to asbestos, but if we decide not to demolish the structures, ongoing problems associated with abandoned buildings will persist (fire hazards, crack houses and other criminal activities, aesthetics, and disease vectors such as rats).

The Home Depot Smart Home at Duke University: Green Materials Processing

Paperless drywall carries a lower risk of developing mold growth. Unfortunately, paperless drywall often requires the use of paints with high levels of VOCs (volatile organic compounds) for surface preparation for finishing. This is a classic example of trade-offs between one engineering option and another. In this case, the exposure to mold and its associated hazards must be balanced against the exposures to coatings and their associated hazards. In addition to being unsightly, hazards from mold include reduced structural integrity of walls and health hazards from the release into the air of toxins that are unsafe to breathe. Complicating risk comparisons between paper and paperless drywall is that the toxins emitted by molds include organic compounds in the vapor phases; so molds are themselves sources of VOCs. Thus, VOCs are agents of concern in both options.

VOC is a catch-all term for organic compounds that partition readily into the air. Generally, these compounds have an affinity for the air under environmental conditions. For example, most VOCs have vapor pressures greater than 10^{-2} kilopascal at 20°C. Some VOCs are distinguishable by their smell, but many of the most toxic compounds are odorless. The health effects depend on the chemical form of the compound. A number of the VOCs are carcinogenic, although in the United States those that are suspected to cause cancer have been removed from paints and coatings. Others have been associated with central nervous system effects (neurotoxins) and other diseases, such as reproductive and developmental problems. Even though consumer products such as paint continue to be reformulated to reduce these hazards, the risks can continue if doses (e.g., the amount inhaled) are higher than disease thresholds. Consequently, in any building, it is wise to minimize exposure to unwanted VOCs as well as to reduce the risk of mold formation.

Mold grows on the cellulose-based paper that is used to cover the faces of most gypsum boards. Most paper is derived from wood, which consists of cellulose, lignin, and other polymeric structures. These organic substances can serve as substrate for microbes, including fungi. That is, they not only provide a place for these organisms to live and grow but also contain the organic compounds that serve as the food sources that provide energy to the fungi. Thus, the choice of using paperless drywall is one technique for reducing the risk of mold formation. When paperless drywall is used, there isn't a ready supply of cellulose for mold to grow on, so the risk of mold formation is lower. Unfortunately, some paperless drywall requires the use of primers that have a large amount of dissolved solids for plugging up holes in the finish. Primers with large amounts of dissolved solids frequently contain lots of VOCs. So it seems at first blush that one must choose between using paperless drywall and using paints that have low amounts of VOCs.

The Home Depot Smart Home at Duke University Solution

Since VOCs are released during coating, the way to strategize for reducing exposures is based on air exchange rates. Thus, the approach is as follows:

1. Use paperless drywall and prime it with a primer that has the minimum recommended amount of dissolved solids.
2. Next, before occupancy, flush the entire building with fresh air every 3 minutes for nine straight days.

This approach takes into account that although VOC concentrations are highest during the time of spraying, they will continue to be released from the sprayed surface for some time. This two-step process flushes out any VOCs that were introduced by the primer, making the air safer for inhabitants.

Questions

1. Draw a life cycle for paperless drywall versus paper drywall. How do extraction and postuse differ?
2. What are the sources of volatile compounds indoors?
3. What does the mass balance look like for formaldehyde? How does it differ from radon?

Source: This example was provided by Tom Rose, Director of the Duke Smart Home Program.

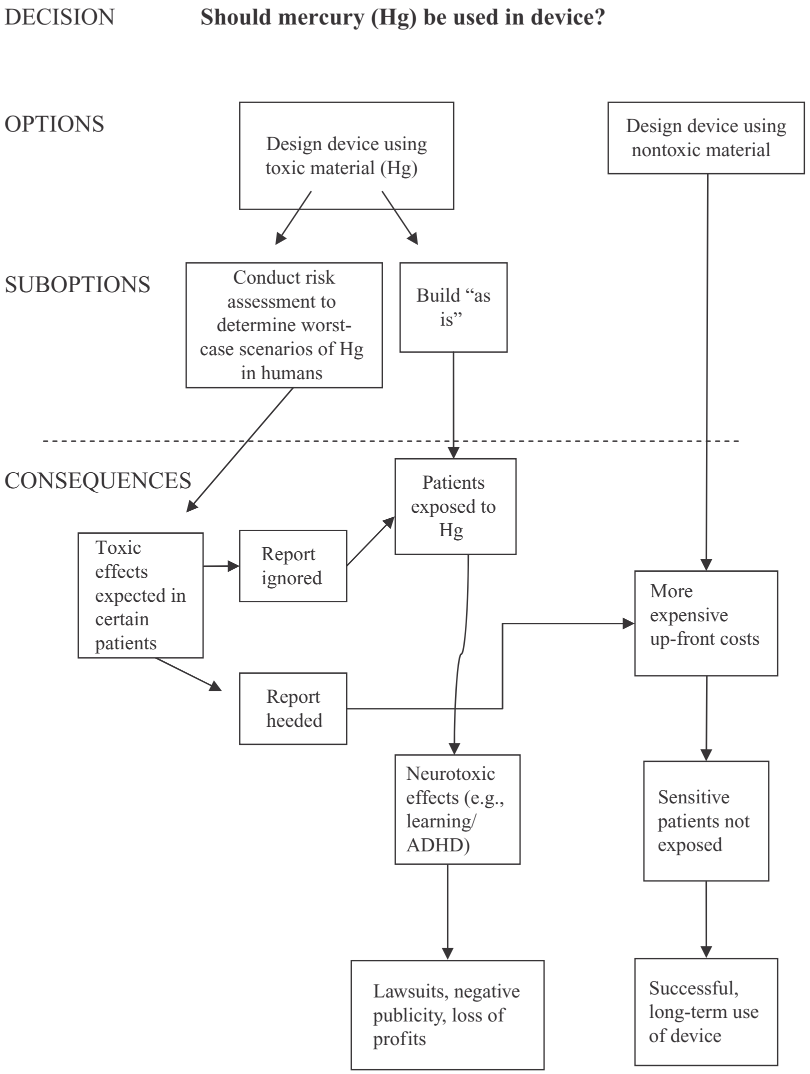

Figure 5.1 Event tree on whether to use mercury in a medical device.

Similarly, green and biomedical engineering may seem to compete against different hazards. For example, the choice of using a toxic substance is complex (see Fig. 5.1). Critical paths, PERT charts, and other flowcharts are commonly used in design and engineering, especially for computing and circuit design. They are also useful in life-cycle analysis if sequences and contingencies are involved in reaching a decision, or if a series of events and ethical and factual decisions lead to the consequence of interest. Thus, each consequence and the decisions made along the way can be seen and analyzed individually and collectively.[1] Other charts need to be developed for safety training, the need for fail-safe measures, and proper operation and maintenance. Thus, a master flowchart can be developed for all of the decisions and subconsequences that ultimately lead to various outcomes from which the designer can choose. Event trees or fault trees allow you to look at possible consequences from each decision. Figure 5.1 provides a simple example.

Designing for the environment (DFE) can be very challenging when there are competing interests and risk trade-offs. This is common in biomedical engineering. Consider, for example, asthma medication that has been delivered to the lungs using a greenhouse gas (GHG) propellant. At first blush the green engineering perspective may forbid it; however, if the total amount of the propellant used in these devices constitutes only 0.0001% of the total GHG used, perhaps the contribution to global warming is considered insignificant. The problem, as illustrated by the Tragedy of the Commons, is that if the cumulative effect of all of the "insignificant" contributions is ignored, collectively they could cause irreversible damage. When it comes to public health trade-offs, the significance is determined by medical efficaciousness. For example, if there are alternatives to this particular GHG that are not greenhouse gases and that are just as effective at delivering the medication, they are preferable from a risk management perspective. As evidence, some asthma medications are now delivered mechanically. If there are no effective alternatives, the trade-off with the environmental effects may be justifiable (see the discussion box "Green Medicine").

Green Medicine

If you have recently attended a medical school hooding ceremony for graduating medical doctors, you may have noticed that the hood is bright green. This symbolizes early medicine's use of herbs and other plants to treat illnesses. Thus, modern medicine's origins are truly green. Recently, medical practice has been rediscovering these roots (pun intended) in a manner similar to that of other technical disciplines. The professions are embracing sustainability.

Medicine and engineering are intimately connected. Some engineering disciplines stand at the interface, particularly biomedical engineering. But most design professions are increasingly affected by health care and its massive infrastructure. This infrastructure includes the classic "hard" design challenges for architects and engineers, such as efficient design of hospitals and other health care facilities, design of state-of-the-science medical devices, and retrofitting antiquated facilities and processes. In fact, obsolescence is increasing exponentially with daily advances in biomedicine, so designers must be agile and adaptive in their designs. Arguably, medical design is arguably the greatest challenge for adaptive designs, since small change, can be the difference between life and death.

There is an apparent conflict between medical and design practitioners, especially in their clients. The engineer's foremost client is the public. The physician's exclusive client is the patient. So there is a question of whether the two perspectives can be reconciled in matters of sustainability. In fact, the medical community is increasingly open to sustainable practices. Notably, the Teleosis Institute has emerged as an organization to support health care professions in service of the global environment. The institute has a mandate to reduce the environmental impacts of health care practices by providing training to support emerging challenges in this area.

The approach is based on the link between human and environmental health. This is not a new concept. Human beings not only affect their environment but are affected by it. The name of the institute reminds as that protection of the environment requires the action of practitioners (*teleosis* is roughly translated from Greek to mean "greater self-realization"). This obligation can be viewed as a form of bioethics, which has numerous definitions. For our purposes, let us define it as the set of moral principles and values (the *ethics* part) needed to respect, to protect, and to enhance life (the *bio* part). Upon review, the definition embodies elements of medicine, health, and biotechnologies. Bioethics is certainly rooted in these perspectives, but bioethics is much more.

Bioethics was coined by Van Rensselaer Potter II (1911–2001). Although Potter was a biochemist, he thought like an engineer: that is, in a rational and fact-based manner. In fact, his original 1971 definition of bioethics was rooted in integration. Potter considered bioethics to bridge science and the humanities to serve the best interests of human health and to protect the environment. In his own words, Potter describes this bridge:

> From the outset it has been clear that bioethics must be built on an interdisciplinary or multidisciplinary base. I have proposed two major areas with interests that appear to be separate but which need each other: medical bioethics and ecological bioethics. Medical bioethics and ecological bioethics are non-overlapping in the sense that medical bioethics is chiefly concerned with short-term views: the options open to individuals and their physicians in their attempts to prolong life. . . . Ecological bioethics clearly has a long-term view that is concerned with what we must do to preserve the ecosystem in a form that is compatible with the continued existence of the human species.*

The Teleosis Institute is putting Potter's view into practice by implementing a new model, *green health care*. The plan calls for health professionals to serve as environmental educators, advocates, and stewards:

*V.R. Potter II, "What does bioethics mean?" *The Ag Bioethics Forum*, 8(1), 2–3, 1996.

> The Teleosis vision of Green Health Care takes us beyond the Hippocratic oath, calling upon health professionals to "do more good." We believe that health professionals—by focusing more on prevention, precaution, education, and wellness—can significantly contribute to improving the health of their patients, community, and the environment.
>
> In Green Health Care, toxic-free buildings, literacy around local environmental health issues, and the use of safe, effective, precaution-based medicine are all intrinsic parts of a new system of health care that is good for people and the environment.*
>
> The institute has identified a number of reasons for the green initiative:

1. Human health is compromised daily by ongoing environmental degradation.
2. Health care must be part of the solution.
3. Green health care improves the health of people and the environment.
4. Green health care is medicine for our future.†

Within design practice and engineering research is a need for balance. This is particularly challenging for biomedical engineering. Society demands that the state-of-the-science be advanced as rapidly as possible *and* that no dangerous side effects ensue. Most engineers have an appreciation for the value of pushing the envelopes of research. They are also adept at optimizing among numerous variables for the best design outcomes. However, emergent areas are associated with some degree of peril. A recent query of top scientists‡ addressed this very issue. Its focus was on those biotechnologies needed to help developing countries. Thus, the study included both the societal and technological areas of greatest potential value (see Table B5.1). Each of these international experts was asked the following questions about the specific technologies:

- *Impact*. How much difference will the technology make in improving health?

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*Teleosis Institute, "Green health care," http://www.teleosis.org/ghc.php; accessed August 10, 2007.

†Ibid.

‡A. S. Daar, H. Thorsteinsdóttir, D. K. Martin, A. C. Smith, S. Nast, and P. A. Singer, "Top ten biotechnologies for improving health in developing countries," *Nature Genetics*, 32, 229–232, 2002.

- *Appropriateness*. Will it be affordable, robust, and adjustable to health care settings in developing countries, and will it be socially, culturally, and politically acceptable?
- *Burden*. Will it address the most pressing health needs?
- *Feasibility*. Can it be developed realistically and deployed in a time frame of 5 to 10 years?
- *Knowledge gap*. Does the technology advance health by creating new knowledge?
- *Indirect benefits*. Does it address issues such as environmental improvement and income generation that have indirect, positive effects on health?

Table B5.1 Ranking by Global Health Experts of the Top Ten Biotechnologies Needed to Improve Health in Developing Countries

Final Ranking	Biotechnology
1	Modified molecular technologies for simple, affordable diagnosis of infectious diseases
2	Recombinant technologies to develop vaccines against infectious diseases
3	Technologies for more efficient drug and vaccine delivery systems
4	Technologies for environmental improvement (sanitation, clean water, bioremediation)
5	Sequencing pathogen genomes to understand their biology and to identify new antimicrobials
6	Female-controlled protection against sexually transmitted diseases, both with and without contraceptive effect
7	Bioinformatics to identify drug targets and to examine pathogen–host interactions
8	Genetically modified crops with increased nutrients to counter specific deficiencies
9	Recombinant technology to make therapeutic products (e.g., insulin, interferons) more affordable
10	Combinatorial chemistry for drug discovery

Source: Data from a survey rported by A. S. Daar, H. Thorsteinsdóttir, D. K. Martin, A. C. Smith, S. Nast, and P. A. Singer, "Top ten biotechnologies for improving health in developing countries," *Nature Genetics*, 32, 229–232, 2002.

The fourth area is clearly the domain of green engineering. However, the others provide some of the constraints within which engineers, green and otherwise, will have to work to advance the state of biomedicine. Engineers as agents of technological progress are at a pivotal position. Technology will continue to play an exponentially increasingly important role in the future. The concomitant societal challenges require that every engineer fully understands the implications and possible drawbacks of these technological breakthroughs. Key among them will be biotechnical advances at smaller scales, well below the cell and approaching the molecular level. Technological processes at these scales require that engineers improve their grasp of the potential ethical implications. The essence of life processes are at stake. Thus, these are the building blocks of green design.

The evolution of green health care in the medical community may follow paths similar to those of the corporate world's embrace of sustainable business practices. Medicine is heavily dependent on technology, so as is true for green engineering and architecture, the medical community's embracing of sustainable approaches will probably be made easier with improved computational abilities and other tools that were not available at the outset of the environmental movement. In fact, it we consider the principles of green engineering described in Table B4.1, a number of biomedical aspects come to the fore (see Table B5.2).

Table B5.2 Green Principles Potentially Applicable to Medicine

Design Principle	Opportunities for Sustainable Biomedicine
Waste prevention	Bioinformatics and data mining can provide candidate syntheses and processes. Such informatics techniques are used increasingly in the medical community. They are not only often more efficient than the old paper-laden searches, but they can provide insights on savings (e.g., energy, less materials, etc.) when complementing life-cycle analysis and environmental management system reviews.

Table B5.2 (*Continued*)

Design Principle	Opportunities for Sustainable Biomedicine
Safe design	Systems biology and "omics" technologies (i.e., genomics, proteomics, and metabonomics) can support predictions of cumulative risk from products used in various scenarios. This can complement risks and opportunities to sensitive populations (e.g., risks to selected polymorphs). It may also allow for more targeted and focused medicines, avoiding wastes that can contribute to cross-resistance and "super bugs."
Low-hazard chemical synthesis	Computational chemistry can help predict unintended product formation and reaction rates of optional reactions. This will prevent downstream toxic waste generation from pharamaceutical and other medical manufacturing processes.
Renewable material use	Systems biology, informatics, and "omics" technologies can provide insights into the possible chemical reactions and toxicity of the compounds produced when switching from depleting to renewable materials. Medical packaging can be more green.
Catalysis	Computation chemistry can help to compare rates of chemical reactions using various catalysts. This not only can prevent downstream waste problems, but may also identify reactions to assist environmental and chemical engineering at the end the process. Reactions identified in the medical research lab may be useful to engineers in treating hazardous wastes (chemical and biological).

(*Continued*)

Table B5.2 (*Continued*)

Design Principle	Opportunities for Sustainable Biomedicine
Avoiding chemical derivatives	Computational methods and natural products chemistry can help scientists start with a better synthetic framework. Prevents unwanted by-products all along the medical critical path, including toxic by-products, as well as microbial processes (e.g., prevention of cross-resistance, antibiotic pass-through treatment facilities, and production of "super bugs," bacteria that are resistant and tolerant of synthetic antibiotics). It can also prevent chiral and enantiomer compounds that are resistant to natural degradation (e.g., left-hand chirals may be much more easily broken down than right-hand chirals of the same compound; also, one chiral may be toxic and the other efficacious).
Atom economy	The same amount of value (e.g., information storage and application) is available on a much smaller scale. Thus, devices are smarter and smaller and more economical in the long term. This not only means they are less hazardous to the patient (e.g., neural implants that are smaller take up less cranial space), but produce less waste overall.
Nanomaterials	Materials that may be used in improved devices and drug delivery systems to support sustainable designs (e.g., nanodevices to monitor environmental quality, nanomaterials to treat medical wastes, and improved laboratory techniques to reduce the generation of bulk and nanoscale wastes). However, the uncertainties about the toxicity of nanomaterials can be a downside.
Selection of safer solvents and reaction conditions	To date, most of the progress has been the result of wet chemistry and bench research. Computational methods will streamline the process, including quicker scale-up in pharmaceutical and other medical manufacturing processes.

Table B5.2 (*Continued*)

Design Principle	Opportunities for Sustainable Biomedicine
Improved energy efficiencies	Heat will always be important in reactions, so green approaches that reduce energy input may lead to greater energy-efficient systems, including intrinsic and extrinsic hazards (e.g., to test certain scale-ups of hydrogen and other economies).
Design for degradation	Medical research can lead the way to better characterization of wastes and improved treatment approaches for those wastes that will be formed (e.g., microbially, photochemical, biochemical).
Real-time analysis to prevent pollution and concurrent engineering	Real-time environmental mass spectrometry and other analytical techniques can be used to analyze whole products, and systems, obviating the need for further sample preparation and analytical steps. This can also include increasing morphological characterizations, such as electron microscopy (e.g., field emission and atomic force).
Accident prevention	Rather than waiting for an accident to occur and conducting failure analyses, medical and design professionals can cooperate to develop concurrent programs to foresee possible conditions conducive to an accident and take steps to prevent them from occurring. Accidents are an example of management failure and inefficiency, so accident prevention is a key part of any sustainable medical program.

Source: Except for "Nano-materials," adapted from U.S. Environmental Protection Agency, "Green chemistry," http://www.epa.gov/greenchemistry/principles.html, 2005, accessed April 12, 2005.

Microethical and Macroethical Green Engineering Perspectives

> The ultimate measure of a man is not where he stands in moments of comfort and convenience, but where he stands at times of challenge and controversy.
>
> Martin Luther King, Jr. (1963)*

Getting back to matching green design with client expectations, we need to consider scale. For example, the green health care initiatives start with a global perspective but place the principal onus for success on the individual health care facility, and ultimately, on the health care provider. Design professionals often characterize phenomena by their dimensions and by when they occur, that is, by their respective *spatial* and *temporal scales*. Design always includes a dimensional analysis by which to measure and describe physical, chemical, and biological attributes of what we design. This analysis is often intuitive and qualitative, but to satisfy the client, the scale must be known at the outset of the design process. So this begs the question: Can we "measure" ethics in a similar way? King's advice is that we *can* measure ethics, especially in our behavior during worst cases. How well can we stick to our principles and duties when things get tough? Philosophers and teachers of philosophy at the university level frequently subscribe to one classical theory or another for the most part, but most concede the value of other models. They all agree, however, that ethics is a rational and reflective process of deciding how we ought to treat each other.

The *engineering profession* has recently articulated its moral responsibility to society to ensure that designs and technologies are in society's best interest. In addition, the *individual engineer* has a specific set of moral obligations to the public and the client. The moral obligations of the profession as a whole are greater than the sum of the individual engineers' obligations. The profession certainly needs to ensure that each of its members adheres to a defined set of ethical expectations. This is a necessary but insufficient condition for the *ethos* of engineering. The "bottom-up" approach of ensuring an ethical engineering population does not completely ensure that many societal ills will be addressed.

Political theorist Langdon Winner has succinctly characterized the twofold engineering moral imperative:

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*M. L. King, Jr., *Strength to Love,* Augsburg Fortress Publishers, Minneapolis, MN, 1963; Fortress ed., May 1981.

> Ethical responsibility . . . involves more than leading a decent, honest, truthful life, as important as such lives certainly remain. And it involves something much more than making wise choices when such choices suddenly, unexpectedly present themselves. Our moral obligations must . . . include a willingness to engage others in the difficult work of defining what the crucial choices are that confront technological society and how intelligently to confront them.*

This engagement necessitates both the bottom-up and top-down approaches.

Most professional ethics texts, including those addressing engineering ethics, are concerned with what has come to be known as *microethics*, which is "concerned with individuals and the internal relations of the engineering profession."† This is distinguished from *macroethics,* which is "concerned with the collective, social responsibility of the engineering profession and societal decisions about technology."‡ Green engineering techniques are examples of microethics. Sustainabilly is an example of macroethics.

Ethical principles are "general norms that leave considerable room for judgment."§ Such principles are codified formally into professional codes of practice. They are also stipulated informally by societal norming, such as by religious, educational, and community standards. In fact, most principles of professional practice are derivative from a small core of moral principles,** which were derived from the lessons learned in biomedical research during the twentieth century:

1. *Respect for autonomy*: allowance for meaningful choices to be made. Autonomous actions generally should be taken intentionally, with understanding and without controlling influences or duress.
2. *Beneficence*: promotion of good for others and contribution to their welfare.

*L. Winner, "Engineering ethics and political imagination," in *Broad and Narrow Interpretations of Philosophy of Technology,* P. T. Durbin, ed., Kluwer Academic, Dordrecht, The Netherlands, 1990, pp. 53–64. Reprinted in D. G. Johnson, ed., *Ethical Issues in Engineering*, Prentice Hall, Englewood Cliffs, NJ, 1991.

†J. E. Herkert, "Microethics, macroethics, and professional engineering societies," in *Emerging Technologies and Ethical Issues in Engineering: Papers from a Workshop*, National Academy of Engineering, October 14–15, 2003, p. 107.

‡Ibid.

§N. Naurato and T. J. Smith, "Ethical considerations in bioengineering research," *Biomedical Sciences Instrumentation*, 39, 573–578, 2003.

**These core principles are articulated by T. L. Beauchamp and J. F. Childress, "Moral norms," in *Principles of Biomedical Ethics*, 5th ed., Oxford University Press, New York, 2001.

3. *Nonmaleficence*: affirmation of doing no harm or evil.
4. *Justice*: the fair and equal treatment of people.

Three of these moral principles were codified in the1979 release of *The Belmont Report: Ethical Principles and Guidelines for the Protection of Human Subjects of Research*.* The U.S. Department of Health and Human Services has summarized the intent of the report:

> The *Belmont Report* attempts to summarize the basic ethical principles identified by the Commission in the course of its deliberations. It is the outgrowth of an intensive four-day period of discussions that were held in February 1976 at the Smithsonian Institution's Belmont Conference Center supplemented by the monthly deliberations of the Commission that were held over a period of nearly four years. It is a statement of basic ethical principles and guidelines that should assist in resolving the ethical problems that surround the conduct of research with human subjects. By publishing the Report in the Federal Register, and providing reprints upon request, the Secretary intends that it may be made readily available to scientists, members of institutional review boards, and federal employees.

The needed changes outlined in the *Belmont Report* resulted from the abuses of Nazi science and, ultimately, the U.S. Public Health Service–sponsored Tuskegee syphilis trials. These travesties led to consensus among the scientific community for the need to regulate research more diligently and to codify regulations to ensure that researchers abide by these principles. The other principle, nonmaleficence, follows ethical precepts required in many ethical frameworks, including harm principles, empathy, and consideration of special populations, such as the infirmed and children.

Thus, green medicine and green engineering, while having different client perspectives, ultimately call for consideration of fairness and openness in practice. Arguably, much of sustainable design and green medicine is about justice. In fact, the environmental justice initiative has evolved along the same time line as that of sustainable design. The two movements are complementary.

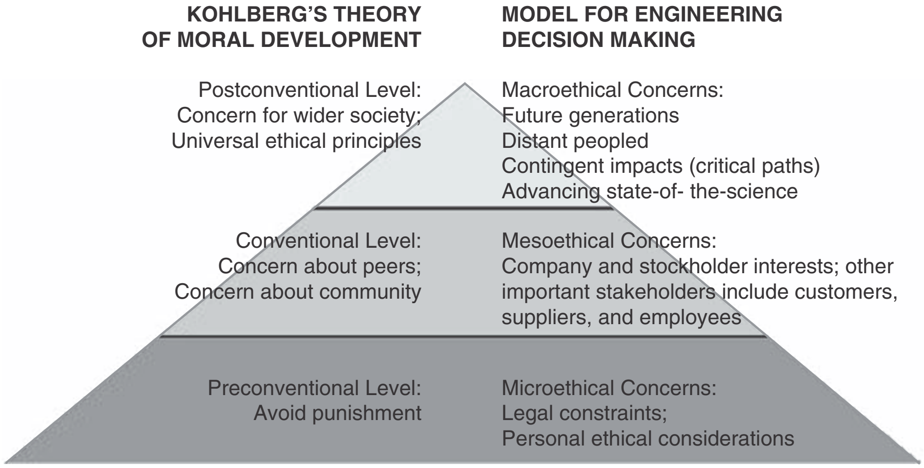
*U. S. Department of Health, Education and Welfare, National Commission for the Protection of Human Subjects of Biomedical and Behavioral Research, *The Belmont Report: Ethical Principles and Guidelines for the Protection of Human Subjects of Research*, April 18, 1979.

JUSTICE: THE KEY TO SUSTAINABLE DESIGN

Cardinal virtues are virtues on which morality hinges (Latin: *cardo*, hinge): justice; prudence; temperance; and fortitude. Among them, justice is the key to sustainability. This is the empathic view and is basic to many faith traditions, notably the Christians' "Golden Rule" and the Native Americans' and Eastern monks' axiom to "walk a mile in another's shoes." Actually, one of commonalities among the great faith traditions is that they share the empathetic precept; for example:[2]

- Judaism, Shabbat 31a, Rabbi Hillel: "Do not do to others what you would not want them to do to you."
- Christianity, Matthew 7, 12: "Whatever you want people to do to you, do also to them."
- Hinduism, Mahabharata XII 114, 8: "One should not behave towards others in a way which is unpleasant for oneself; that is the essence of morality."
- Buddhism, Samyutta Nikaya V: "A state which is not pleasant or enjoyable for me will also not be so for him; and how can I impose on another a state that is not pleasant or enjoyable for me?"
- Islam, Forty Hadith of an-Nawawi, 13: "None of you is a believer as long as he does not wish his brother what he wishes himself."
- Confucianism, Sayings 15:23: "What you yourself do not want, do not do to another person."

Professional competence can take us in the right direction. As professionals, we must excel in what we know and how well we do our technical work. This is a necessary requirement of the engineering experience, but it is not the only part. Engineering schools have increasingly recognized that engineers need to be both competent and socially aware. The ancient Greeks referred to this as *ethike arêtai* ("skills of character"). The competence of the professional engineer is inherently linked to character. Even the most competent engineer, architect, or physician is not really acting professionally unless he or she practices ethically. By extension, our care for others and their just treatment requires that we use the resources and gifts of our calling in a way that ensures a livable world for future and distant people. This is the essence of sustainable design.



re 5.2 Adaptation of
berg's stages of moral
lopment to the ethical
ctations and growth in the
neering profession.

D. A. Vallero, *Biomedical Ethics
gineers: Ethics and Decision
ng in Biosystem and Biomedical
eering*, Academic Press, San
, CA, 2007.

EVOLUTION OF RESPONSIBLE CONDUCT

Educational psychologists argue that moral development takes a predictable and stepwise progression. The development is the result of social interactions over time. For example, Kohlberg[3] identified six stages in three levels, wherein every person must pass through the preceding step before advancing to the next. Thus, a person first behaves according to authority (stages 1 and 2), then according to approval (stages 3 and 4), before finally maturing to the point where they are genuinely interested in the welfare of others. Our experience has been gratifying in that most colleagues and engineering students enrolled in our courses have indicated moral development well within the postconventional level.

We can apply the Kohlberg model directly to the engineering profession (see Fig. 5.2). The most basic (bottom tier) actions are preconditional. That is, engineering decisions are made solely to stay out of trouble. While proscriptions against unethical behavior at this level are effective, the training, mentorship, and other opportunities for professional growth push the engineer to higher ethical expectations. This is the normative aspect of professionalism. In other words, with experience as guided by observing and emulating ethical role models, the engineer moves to conventional stages. The engineering practice *is* the convention, as articulated in our codes of ethics. This is why it is so important when the professional code of ethics is revised, such as when the American society of civil Engineers added a sustainability clause some years ago.

Above the conventional stages, the truly ethical engineer makes decisions based on the greater good of society, even at personal costs. In fact, the "payoff" for the engineer in these cases is usually for people he or she will never meet and may occur in a future that he or she will not share personally. The payoff does provide benefits to the profession as a whole, notably that we as a profession can be trusted. This top-down benefit has incremental value for every engineer. Two common sayings come to mind about top-down benefits. Financial analysts often say about the effect of a growing economy on individual companies: "A rising tide lifts all ships." Similarly, environmentalists ask us "to think globally, but act locally." In this sense, the individual engineer or design professional is an emissary of the profession, and the profession's missions include a mandate toward sustainability.

Research introduces a number of challenges that must be approached at all three ethical levels. At the most basic, *microethical* level, laws, rules, regulations, and policies dictate certain behaviors. For example, environmental research, especially that which receives federal funding, is controlled by rules overseen by federal and state agencies. Such rules are often proscriptive, that is, they tell you what *not to do*, but are less clear on what actually *to do*. Also, establishing a legal threshold is not necessarily the "right" thing to do.

At the next level, beyond legal considerations, the engineer is charged with being a loyal and faithful agent to the clients. Researchers are beholden to their respective universities and institutions. Engineers and architects working in companies and agencies are required to follow mandates to employees (although never in conflict with their obligations to the engineering profession). Thus, engineers must stay within budget, use appropriate materials, and follow best practices as they concern their respective designs. For example, if an engineer is engaged in work that would benefit from collaborating with another company working with similar genetic material, the engineer must take precautionary steps to avoid breeches in confidentiality, such as those related to trade secrets and intellectual property.

The highest level, the *macroethical* perspective, has a number of aspects. Many of the research and development projects address areas that could greatly benefit society but may lead to unforeseen costs. The engineer is called to consider possible contingencies. For example, if an engineer is designing *nanomachinery* at the subcellular level, is there a possibility that self-replication mechanisms in the cell could be modified to lead to potential adverse effects, such as generating mutant pathological cells, toxic by-products, or changes in genetic structure not previously expected? Thus, this highest level of professional development is often where *risk trade-offs* must be considered. In the case of our example, the risk of adverse genetic outcomes must be weighed against the loss of advancing the state of medical science (e.g., finding nanomachines that manufacture and deliver tumor-destroying drugs efficiently). Genetically modified food is another example of such trade-offs.

Ongoing cutting-edge research (such as the efficient manufacturing of chemicals at the cellular scale, or the development of cybernetic storage and data transfer systems using biological or biologically inspired processes) will create new solutions to perennial human problems by designing more effective devices and improving computational methodologies. Nonetheless, in our zeal to push the envelopes of science, and design we must not ignore some of the larger, societal repercussions of our research and advances is design techniques; that is, we must employ new paradigms of macroethics.

William A. Wulf, president of the National Academy of Engineering, introduced the term *macroethics*, defining it as a societal behavior that increases the intellectual pressure "to do the right thing" for the long-term improvement of society. Balancing the potential benefits to society of advances in biotechnology and nanotechnology while also avoiding negative societal consequences is a type of macroethical dilemma.[4] Macroethics asks us to consider the broad societal impact of science in shaping research agendas and priorities. At the same time, microethics is needed to ensure that researchers and practitioners act in accordance with scientific and professional norms, as dictated by standards of practice, community standards of excellence, and codes of ethics.[5] The engineering profession and engineering education standards require attention to both the macro and micro dimensions of ethics. Criterion 3, "Program Outcomes and Assessment" of the Accreditation Board for Engineering and Technology, Inc. (ABET), includes a basic microethical requirement for engineering education programs, identified as "(f) an understanding of professional and ethical responsibility," along with macroethical requirements that graduates of these programs should have "(h) the broad education necessary to understand the impact of engineering solutions in a global and societal context" and "(j) a knowledge of contemporary issues."[6]

CONCURRENT DESIGN

Medical device design can parallel green design. One technique used to develop and adapt devices is concurrent engineering, which is a systematic approach that integrates numerous elements and advances the design process in a parallel manner as we advocate in our synthovation model rather than in a serial sequential approach. This should sound similar to the sustainable design approach. In fact, the Software Engineering Institute of Carnegie Mellon University includes the life-cycle perspective in its definition of *concurrent engineering*: "a systematic approach to integrated and concurrent development of a product and its related processes. Concurrent engineering emphasizes response to customer expectations and embodies team values of cooperation, trust, and sharing-decision making proceeds with large intervals of parallel work by all life-cycle perspectives, synchronized by comparatively brief exchanges to produce consensus."[7]

Sidebar: Applying the Synthovation/Regenerative Model: Concurrent Engineering

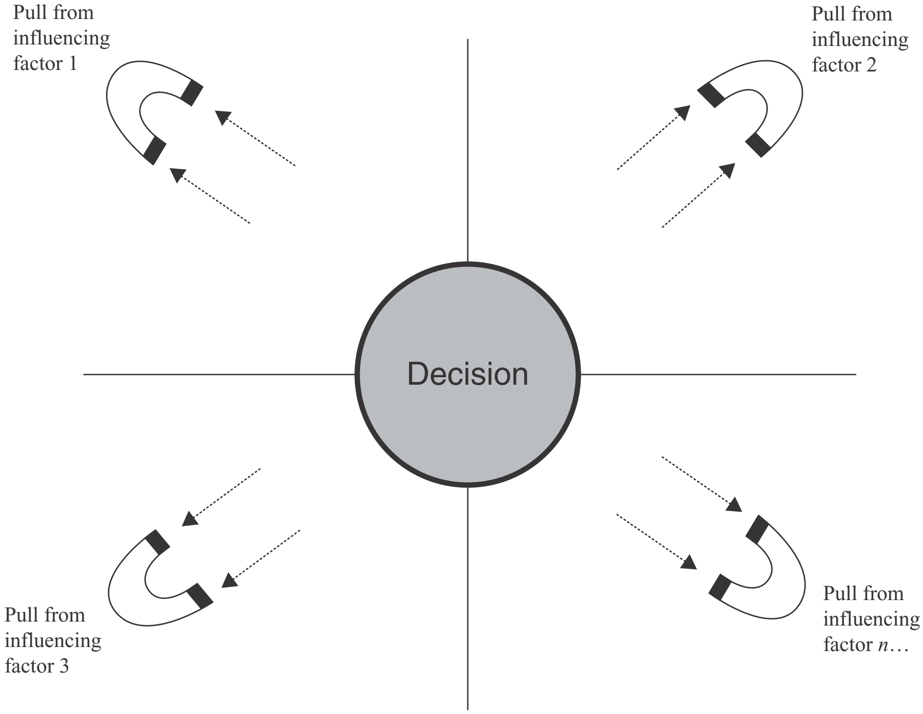
Concurrent engineering is a type of integrative design. It can be envisioned in the form of rapidly revolving teams. The typical design process, (described in Chapter 1) for example, is stepwise. Different departments must complete their responsibilities before passing their interim piece of the design process on to the next department. There are at least two problems with this approach. The department is likely not to know much about the details of the process that took place before they received their charge. Also, they may well believe that their work is *done* as soon as they pass their work along. Concurrent engineering allows for myriad points of view and keeps various team members involved from start to finish.

The advantage of concurrent engineering is its integration of multiple perspectives. It is an integrative way to design to meet a client's needs. It prevents the common problems of the sequential, stepwise approach (type 1, discussed in Chapter 1), replacing it with parallel processes with immediate consideration for every aspect of what it takes to produce a product. A design team is tailored to meet the client needs by optimizing the skills and other corporate resources to work with a common approach to meet specific design criteria. As such, concurrent engineering leverages the expertise, the synergy, and creativity of a design team made up of multiple perspectives. Experts in design, technology, manufacturing, operations, and other disciplines work simultaneously with a single purpose.

The challenge of concurrent engineering is that it requires an "all in" perspective. The agency or firm must be dedicated to the long-term implementation, evaluation, and updates and continuous enhancements. This can be very different from the sequential flow of most designs. It can also be daunting at first, since the team approach is very different from that of the hierarchical structures of many organizations. Thus, it needs commitment from upper management to support a new set of measures of success as well as a buy-in from every team member and the parts of the organization that they represent.

Green design actually has been one of the movements toward concurrent design. Few, if any, green design decisions can be made exclusively from a single perspective. We can visualize these design decisions as attractions within a force field, where the center of the diagram represents the initial condition with a magnet placed in each sector at points equidistant from the center of the diagram (see Fig. 5.3). If the factors are evenly distributed and weighted, the diagram might appear as in Figure 5.4. But as the differential among

Figure 5.3 Decision force field. The initial conditions will be driven toward influences. The stronger the influence of a factor (e.g., medical efficacy), the greater the decision will be drawn to that perspective.



magnetic forces increases, the relative intensity of each factor will drive the decision progressively. The decision is distorted toward various influences. So in our greenhouse gas propellant example, the medical efficacy drives the decision (Fig. 5.5). The stronger the magnet, the more the decision that will actually be made will be pulled in that direction. Thus, in greening hospitals, for example, physicians and clinical engineers may drive the decision in one direction; lawyers may pull in another direction, and environmental professionals and green designers may pull in a different direction. The net effect is a decision that has been "deformed" in a manner unique for that decision and that must be considered by the designer.

Thus, the harm must be considered comprehensively. By their very nature, design professionals are risk managers. All design decisions are made under risk and uncertainty (that is why factors of safety are a part of every recommendation). The risk management process is informed by the quantitative results of the risk assessment process. The shape and size of the resulting decision force field diagram give an idea of the principal driving factors that lead to decisions. Therefore, the force field diagram can be a useful, albeit subjective tool to visualize initial conditions, boundary conditions, constraints, trade-offs, and opportunities.

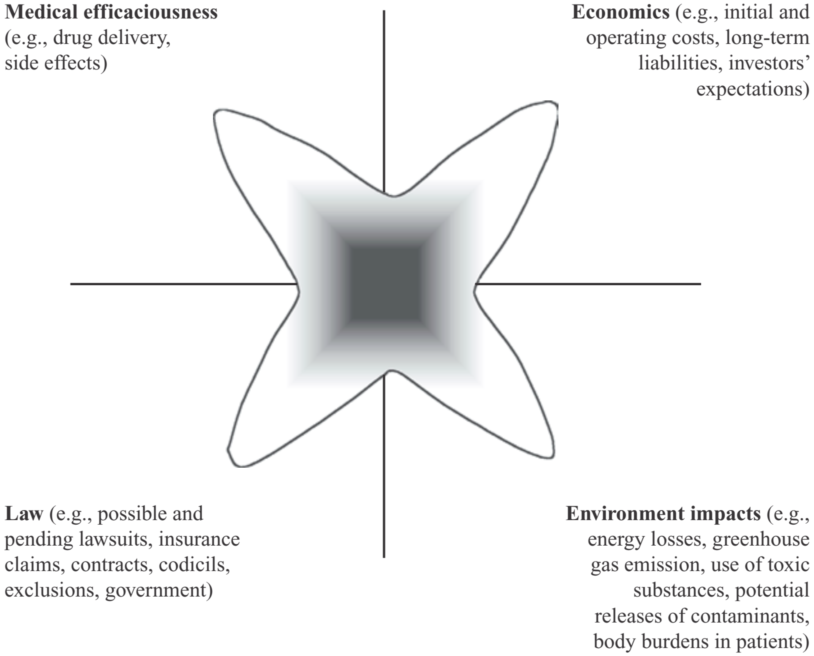


Figure 5.4 Decision force field where a number of factors have nearly equal weighting in a design decision. For example, if the law is somewhat ambiguous, a number of medical alternatives are available, costs are flexible, and environmental impacts are reversible, the design has a relatively large degree of latitude and elasticity.

BENCHMARKING

Sustainable design must account for the various spheres of influence in the life cycle, including the technical intricacies involved in manufacturing, using and decommissioning of a product or system, the infrastructure technologies needed to support the product and the social structure in which the product is made and used (see Fig. 5.6). This means that no matter how well a product is manufactured, with the best quality control and assurances, it may well fail if the infrastructure and societal context is not properly characterized and predicted. Each of the spheres in Figure 5.6 affect and are influenced by every concentric sphere.

Decision force fields can be adapted specifically to sustainable designs. For example, if we are concerned primarily about toxic management, we can develop decision force fields based on the various physical and chemical properties of a substance using a multiple-objective plot (Fig. 5.7). In this plot two different products can be compared visually in terms of the sustainability, based on toxicity (e.g. carcinogenicity), mobility and partitioning (e.g., sorption, vapor pressure, Henry's law constants), persistence, and treatability by different methods (e.g., wastewater treatment facilities, pump and treat). The shape of the curve and the size of the peaks are relative indicators of toxicity and persistence of a potential problems (the inverse of sustainability of healthy conditions).

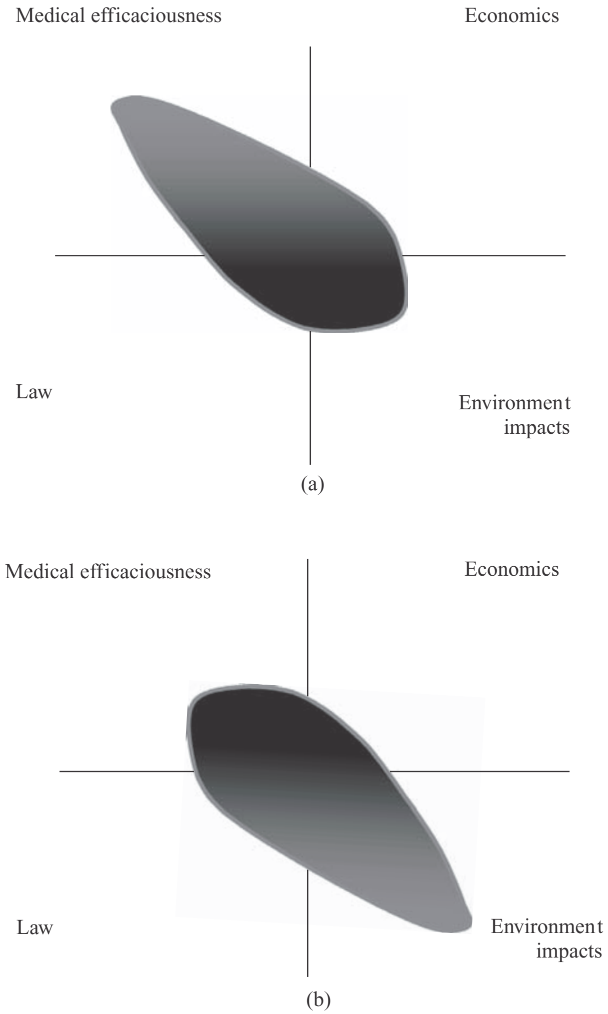


Figure 5.5 Decision force field driven predominantly by one or a few factors. For example, if mortality or serious disease will increase, medical efficacy holds primacy over environmental, financial, and even legal considerations (a). Legality is complex. At least ideally, the law protects public safety, health, and welfare (the three mandates of the engineering profession). Thus, it may embody aspects of the other sectors (e.g., medical beneficence, environmental protection, cost accountability). If medical efficacy is flexible and can be achieved in a number of ways but environmental impacts are substantial, irreversible, and/or widespread, the design will be driven to be greener (b). Note that in both diagrams, all of the factors have some force; that is, the factors are important, just not as influential as the stronger factors.

The plot criteria are selected to provide an estimate of the comparative sustainability of candidate products. It is important to tailor the criteria to the design needs. In the case of Figure 5.7, this addresses primarily the toxic hazard and risk of the substances:[8]

- *Vapor pressure*: a chemical property that tells us the potential of the chemical to become airborne. The low end of the scale is 10^{-8} mmHg; the high end is 10^{2} mmHg and above.
- *Henry's law*: tells us how the chemical partitions in air and water. Nonvolatile substances have a value of 4×10^{-7} (unitless), moderate volatility is between

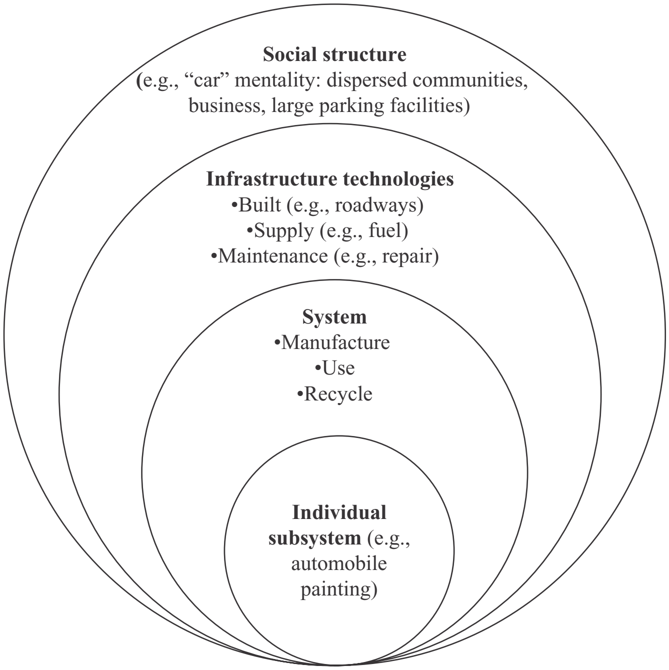


Figure 5.6 Spheres or layers of influence in a system. The system consists of interdependencies among each layer.

Adapted from: B. R. Allenby and T. E. Graedel, *Industrial Ecology*, Prentice Hall, Upper Saddle River, NJ, 1995.

4×10^{-4} and 4×10^{-2}, and volatile chemicals are at or above 4. The values are limitless because they are a ratio of concentration in air and water.

- *Solubility*: the potential of the chemical to enter water. Very soluble chemicals are on the order of 10,000 ppm and nonsoluble entities have a solubility of less than 0.1 ppm.
- *Bioconcentration*: the tendency/potential of the chemical to be taken up by biological entities (algae, fish, animals, humans, etc.). A low potential is defined as 250 (unitless) or less, while a high potential is found at 1000 or above.
- *Atmospheric oxidation* (half-life, days): helps to define the fate of the chemical once it enters the atmosphere. A short half-life is desirable, as the chemical will have little time to cause adverse effects. A rapid half-life would be on the order of 2 hours or less. A slow half-life is between 1 and 10 days; longer than 10 days is a persistent chemical.
- *Biodegradation*: the ability of the environment to break down the chemical. A short biodegradation time is ideal so that the chemical does not persist. There are two sectors of biodegradation; one is dimensionless and one has units of time. A biodegradation factor on the order of hours is very quick, whereas a factor on the order of years is long.

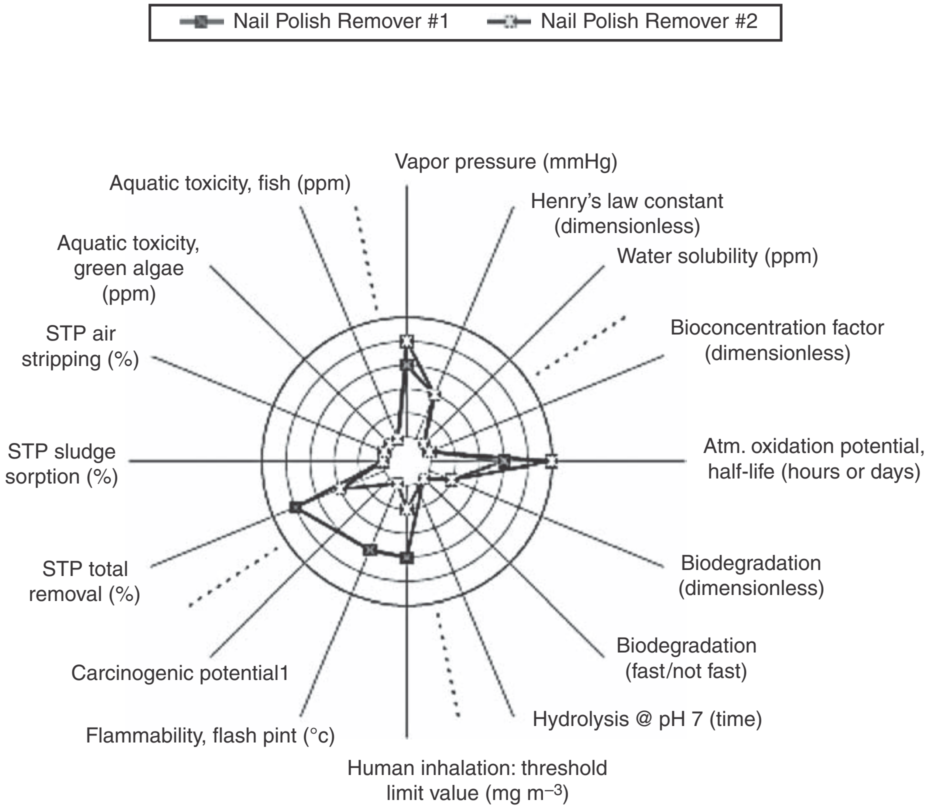


Figure 5.7 Multiple-objective plot of two candidate chemical mixtures to be used to remove fingernail polish from consumers. Both products appear to have an affinity for the air. Product 1 has a larger half-life (i.e., is more persistent), whereas product 2 is more carcinogenic, flammable, and likely to be taken up by the lungs. Based on these factors, it appears, at least at the screening level, that product 1 is comparatively better from a sustainability standpoint.

- *Hydrolysis*: the potential of the chemical to be broken down into a by-product and water. It has units of time for a pH of 7. A long hydrolysis time is on the order of many years.
- *Flammability*: the chemical's flash point (°C).
- *Human inhalation*: the threshold limit for inhalation of the chemical below which there will be no observed effect in humans. A value of 500 mg m^{-3} and above is a high concentration for which there is little effect. The chemical becomes more of a problem when the limit is 50 mg m^{-3} or less.
- *Carcinogenicity*: the potential for the chemical to cause cancer. These data are usually somewhat uncertain, due to inaccurate dose–response curves.
- *STP total removal*: the percent of the chemical that is removed in a wastewater treatment process. A removal value 90 to 100% is desirable, whereas 0 to 10% removal describes a chemical that is tough to treat.

Table 5.1 Functions That Must Be Integrated into an Engineering Design

1. Baseline studies of natural and built environments
2. Analyses of project alternatives
3. Feasibility studies
4. Environmental impact studies
5. Assistance in project planning, approval, and financing
6. Design and development of systems, processes, and products
7. Design and development of construction plans
8. Project management
9. Construction supervision and testing
10. Process design
11. Startup operations and training
12. Assistance in operations
13. Management consulting
14. Environmental monitoring
15. Decommissioning of facilities
16. Restoration of sites for other uses
17. Resource management
18. Measuring progress for sustainable development

Source: American Society of Mechanical Engineers, http://www.professionalpractice.asme.org/communications/sustainability/2.htm, accessed May 23, 2006.

- *STP sludge sorption*: the percentage of how much of the chemical will adsorb to the sludge in a wastewater treatment plant (WWTP). This can be important when the sludge is disposed in a landfill or is agriculturally land applied. A sorption value of 0 to 10% is ideal so that the chemical doesn't get recycled back to the environment; 90 to 100% sorption to sludge solids makes disposal difficult.

- *STP air removal*: the percentage of the chemical that is removed to the air from WWT. A value of 0 to 10% is ideal so that little extra air treatment is needed; 90 to 100% air removal requires significant air treatment.

- *Aquatic Toxicity* (green algae) (ppm): the chemical's toxicity to green algae. A toxic effect on algae can disrupt the entire food chain of an ecosystem. Toxicity is measured on a concentration scale. A low toxicity would be at high concentrations (>100 ppm). A high toxicity would be at concentrations on the ppb or ppt scale.

- *Aquatic toxicity* (fish) (ppm): the toxicity of the chemical to a specific fish species. For example, in the Pacific Northwest, a chemical that is toxic to salmon can cause millions of dollars in economic damage. A low toxicity would be at high concentrations (>100 ppm). A high toxicity would be at concentrations on the ppb or ppt scale.

Certainly, green design considers more than toxicity. So other alternatives for recycling and reuse, avoiding consumer misuse, and disassembly can also be compared with multiple objective plots. The best of these can be considered the benchmark, which is a type of index that conveniently displays numerous factors with appropriate weightings.

Another way to visualize such complex data is the decision matrix. The matrix helps the designer to ensure that all of the right factors are considered in the design phase and that these factors are properly implemented and monitored throughout the project. Integrated engineering approaches require that

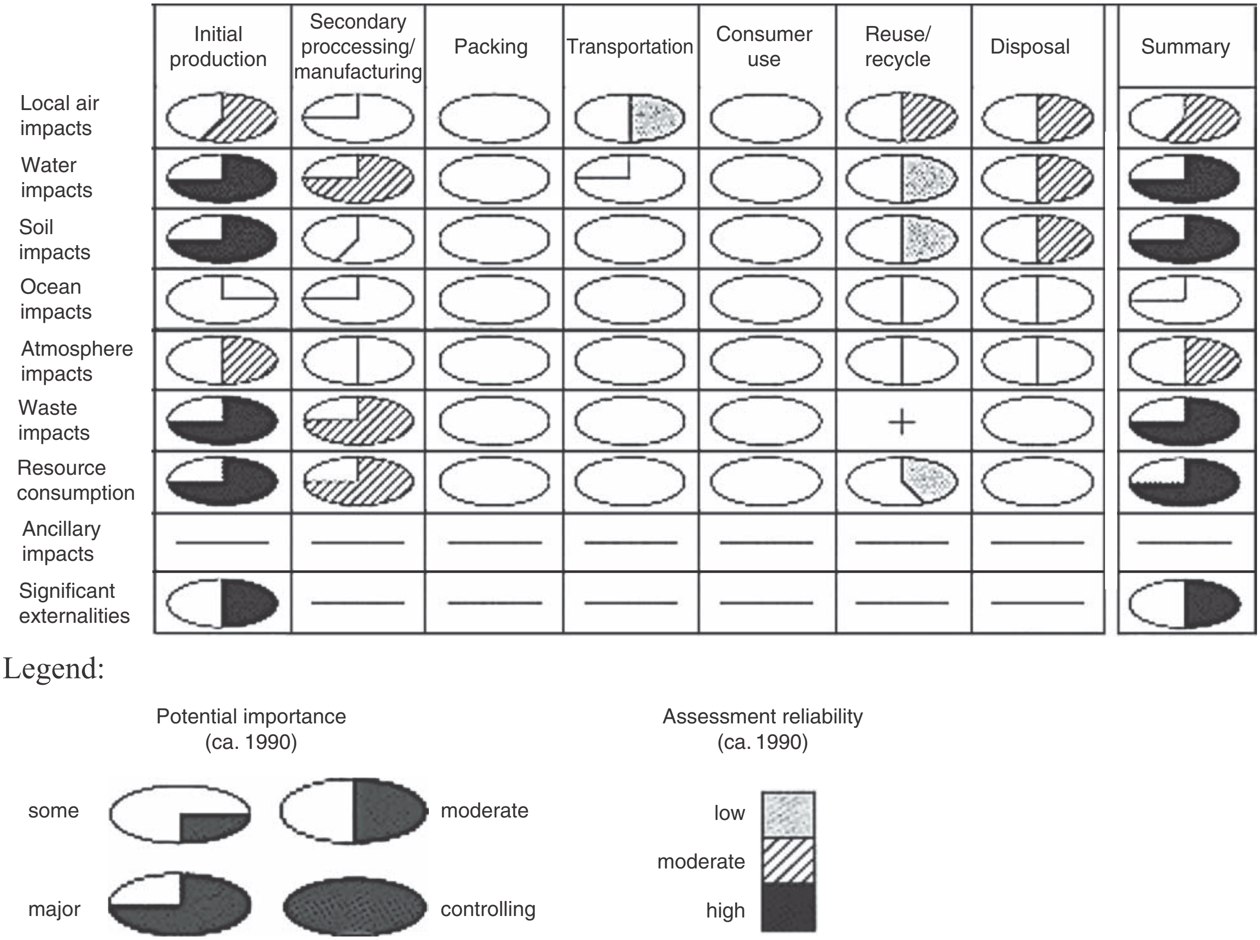
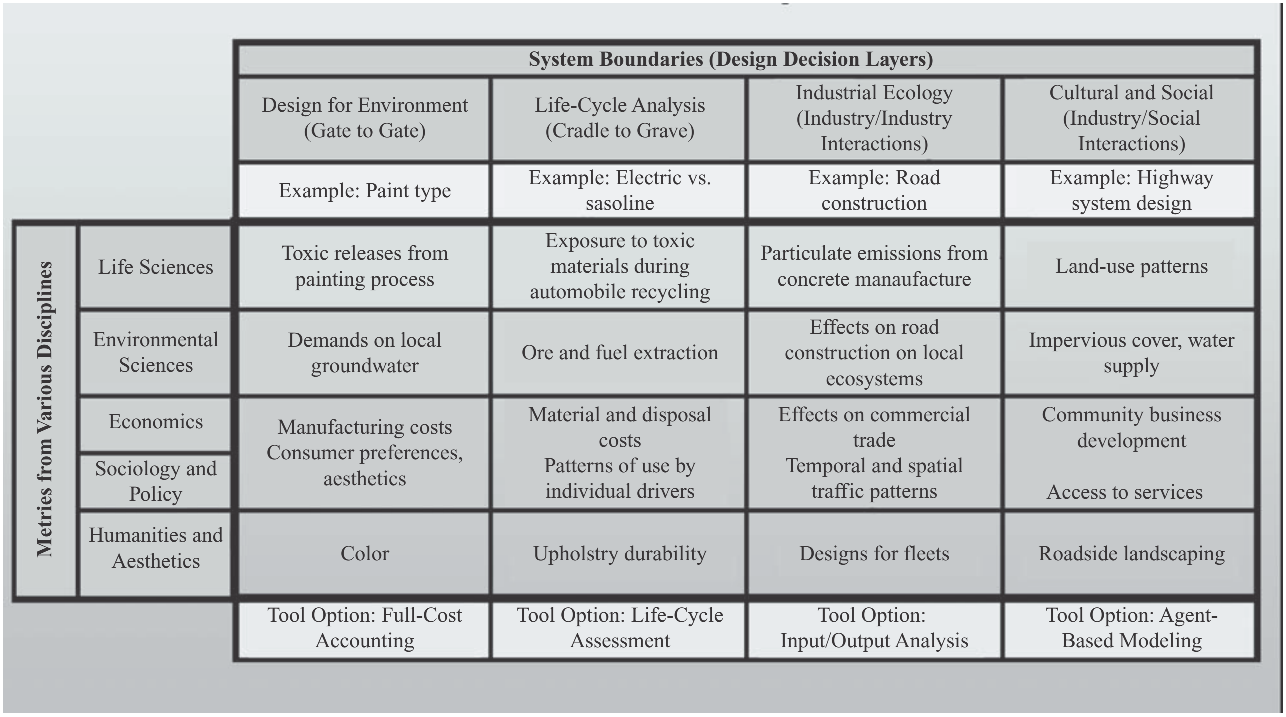


Figure 5.8 Example of an integrated engineering matrix: in this instance, applied to sustainable designs.

From American Society of Mechanical Engineers, http://www.professionalpractice.asme.org/communications/sustainability/2.htm, accessed May 25, 2006).



		System Boundaries (Design Decision Layers)			
		Design for Environment (Gate to Gate)	Life-Cycle Analysis (Cradle to Grave)	Industrial Ecology (Industry/Industry Interactions)	Cultural and Social (Industry/Social Interactions)
		Example: Paint type	Example: Electric vs. sasoline	Example: Road construction	Example: Highway system design
Metries from Various Disciplines	Life Sciences	Toxic releases from painting process	Exposure to toxic materials during automobile recycling	Particulate emissions from concrete manaufacture	Land-use patterns
	Environmental Sciences	Demands on local groundwater	Ore and fuel extraction	Effects on road construction on local ecosystems	Impervious cover, water supply
	Economics	Manufacturing costs Consumer preferences, aesthetics	Material and disposal costs Patterns of use by individual drivers	Effects on commercial trade Temporal and spatial traffic patterns	Community business development Access to services
	Sociology and Policy				
	Humanities and Aesthetics	Color	Upholstry durability	Designs for fleets	Roadside landscaping
		Tool Option: Full-Cost Accounting	Tool Option: Life-Cycle Assessment	Tool Option: Input/Output Analysis	Tool Option: Agent-Based Modeling

Figure 5.9 Matrix proposed by D. Allen to evaluate various green design techniques with respect for science, social, and economic metrics.

the engineer's responsibilities extend well beyond the construction, operation, and maintenance stages. Such an approach has been articulated by the American Society of Mechanical Engineers (ASME). The integrated matrix helps DFE to be visualized, as recommended by the ASME[9] (see Table 5.1). This allows for the engineer to see the technical and ethical considerations associated with each component of the design as well as the relationships among these components. For example, health risks, social expectations, environmental impacts and other societal risks and benefits associated with a device, structure, product, or activity can be visualized at various stages of the manufacturing, marketing, and application stages. This yields a number of two-dimensional matrices (see Fig. 5.8) for each relevant design component. And each respective cell indicates both the importance of that component and the confidence (expressed as scientific certainty) that the engineer can have about the underlying information used to assess the importance (see the Figure 1.5 legend). Thus, the matrix is a visualization of the life cycle, or at least substantial portion of it.

The matrix approach is qualitative or at best semiquantitative, but like multiple-objective plots, provides a benchmark for comparing alternatives that would otherwise be incomparable. To some extent, even numerical values can be assigned to each cell to compare them quantitatively, but the results are at the discretion of the analyst, who determines how different areas are weighted. The matrix approach can also focus on design for a more specific measure, such as energy efficiency or product safety, and can be extended to corporate activities as a system.

David Allen, on the faculty of the University of Texas, is a leader in industrial ecology and sustainable design. He has proposed another matrix for benchmarking (see Fig. 5.9). Since sustainable design can be achieved by numerous approches, this matrix compares the system's boundaries or the layers shown in Figure 5.6 to the types of factors we included in our decision force fields (Figs. 5.3 and 5.4). Expected outcomes and impacts are shown in the corresponding cells of the matrix. The rows determine which type of green design tool should be used: full-cost accounting, life-cycle analysis, input/output analysis, or agent-based modeling.

The key point about benchmarking is the importance of a prospective viewpoint in design. Whatever tools we can use to help us to model and to predict consequences of available alternatives is an important aspect of green design.

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chapter 6

The Sustainability Imperative

Warning: We get a bit philosophical in this chapter!

In Chapter 5, we allowed ethics to help to set the stage for green design and the means for optimizing among disparate design criteria. Let us go one step further. The philosopher Immanuel Kant is famous for the categorical imperative, which says that the right thing to do requires that a person must "act only on that maxim whereby thou canst at the same time will that it should become a universal law."[1] In other words, in deciding whether an act is right or wrong, it is our duty to think about what would happen if everyone acted in the same way. This should sound familiar to those of us concerned about the environment and public health. In fact, it is the essence of sustainability. The only way to ensure that something is protected for the future is to think through all of the possible outcomes and select only those that will sustain a better world.

Kant's imperative is the rationale that underpins environmental mottos:

- Think globally, act locally.
- We are not going to be able to operate Spaceship Earth successfully or for much longer unless we see it as a whole spaceship and our fate as common. It has to be everybody or nobody. (This was articulated first by R. Buckminster Fuller.)
- Now, as never before, the old phrase has a literal meaning: We are all in the same boat. (The musings of Jacques Cousteau)
- When one tugs at a single thing in nature, he finds it attached to the rest of the world. (The philosophy of John Muir)

- A thing is right when it tends to preserve the integrity, stability, and beauty of the biotic community. It is wrong when it tends otherwise. (Aldo Leopold's "Land Ethic")
- Nothing ever goes away. (Barry Commoner's admonition against the "throw away" society)
- Only within the moment of time represented by the present century has one species—man—acquired significant power to alter the nature of his world. (Rachel Carson's fear of an impending *silent spring*).

And even a few folks who are not likely to be called "environmentalists" have supported the need for a sustainable and universalizable approach to society's challenges:

- Our ideals, laws, and customs should be based on the proposition that each generation, in turn, becomes the custodian rather than the absolute owner of our resources and each generation has the obligation to pass this inheritance on to the future. (Charles Lindbergh, *New York Times Magazine,* 1971)
- There is no silver bullet. . . . The important criteria are reliability, . . . is it affordable? . . . We need to use fuels that have minimal emissions of greenhouse gases. . . . (James Rogers, President and Chief Executive Officer of Duke Energy)
- You and I have a rendezvous with destiny. We will preserve for our children this, the last best hope of man on earth, or we will sentence them to take the first step into a thousand years of darkness. (President Ronald Reagan)

GREEN PRACTICE AND THE CASE FOR SUSTAINABLE DESIGN

In this book we describe the approaches and techniques available to designers to shape a more sustainable existence on Earth. An additional focus, one that is unique among most design guidebooks, is to explain the underpinning science that allows such approaches and techniques to work. We "close the loop" by enhancing the designer's understanding of these processes and cycles of nature. This leads to a deeper understanding of systems that operate once the design is implemented and, ideally, forms a foundation for the exploration and discovery of innovative ways to minimize risks to health and safety, increase design reliability, and reduce our ecological footprint. With a better understanding of sustainable processes, new strategies will emerge to supplant old ways of thinking, especially replacing those antiquated templates that depend on the subjugation of nature to achieve human ends.

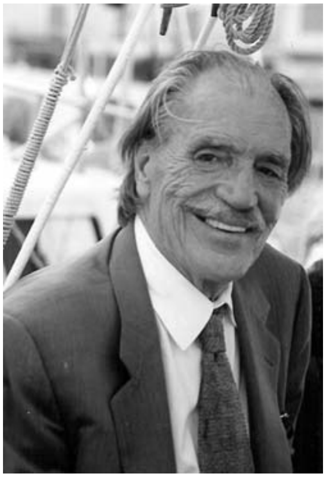

Figure 6.1 Ian McHarg.

Courtesy of Carol McHarg.

From the outset, we have argued that understanding the physical world depends on a foundation in the laws of thermodynamics and motion. All engineering and architectural curricula are built on this foundation. However, over the past few decades, designs have become more adaptive. One noteworthy sea change was the movement to "design with nature." How important the preposition "with" was to become to the design professions! The last three decades of the twentieth century approached nature as a collaborator, not an opponent. In fact, in the groundbreaking 1969 book entitled *Design with Nature*,[2] Ian McHarg (see Fig. 6.1) urged planners to conform to ecology rather than to compete with it. The book, which has sold more than 250,000 copies, has been likened to other influential environmental works, including those by Lewis Mumford, Rachel Carson, even going back to Henry David Thoreau.

Vallero recalls in the mid-1970s using the book in his urban planning and design graduate courses and being particularly struck by the profound yet simple use of overlays (stacked Mylar maps). A transparency was prepared for each attribute, such as wetlands, littoral vulnerability, urbanization, sensitive forests, or water supplies. By overlaying different attributes (transparencies) atop each other, patterns would become obvious, such as areas that needed special protection from development. In fact, McHarg was a prominent critique of the close-mindedness of many engineering project, such as highway planning (referring to the road designers as "highwaymen").

The elevated environmental consciousness that emerged from the upheavals of the 1960s has led to many benefits. These are evidenced by the myriad legislation, regulation, treaties, codes and ordinances that have given us a cleaner world. However, one negative side effect is the growth of "junk science" in environmentalism. Of course, not all environmentalism depends on weak and unsound science, but too much is unsupported by the principles of physics, chemistry, and biology. The authors can attest that the good news is that many of the methods of green chemistry, green engineering, and sustainable design are indeed supportable by sound science. The problem has been that many methods and much thinking have not undergone the scientific scrutiny called for since the Renaissance, when Robert Boyle and the Royal Society instituted the rules of a posteriori science. Too many cases for the environment have been taken as the articles of faith of environmentalism. Thus, if we want to take the Kantian view, we must ensure that *all* designs are founded on strong scientific principles.

Social Responsibility: The Ethical and Social Dimensions of Sustainable Design

Few topics are more current than those related to sustainable design. Former Vice President Al Gore received an Oscar for *An Inconvenient Truth* and most recently shared the Nobel Peace Prize with the Intergovernmental Panel on Climate Change (IPCC). Kindergartners fear the demise of the polar bear due to global warming. High school students calculate their "carbon footprints." The majority of scientists concur that Earth is warming and endorse the most recent report by the IPCC, which states that Western nations, especially the United States, need to make major reductions in their emissions of global greenhouse gases, especially carbon dioxide.

Whether they like it or not, scientists are influencing policies. Most are uncomfortable outside their specific discipline. Few are trained in matters of politics, journalism, and mass communication. In fact, many scientists argue that their single calling is to adhere to the scientific method and to let others worry about how such knowledge is put to use. However, it is likely that only a small subset of these scientists see a complete divorce of science and policy. For example, even those who are conducting basic research should worry that their advances may be put to some evil use. This is the "dual-use" dilemma, where something designed for beneficial outcomes (e.g., understanding the structure of the atom) is used in ways not intended by the researcher (e.g., terrorists' construction of a "dirty bomb"). That said, scientists are required to conduct research responsibly; and at the top of the list of responsible conduct is that of seeking and telling the truth. This view was best articulated by a famous twentieth-century philosopher of science, C. P. Snow, into a single tenet of science: "The only ethical principle which has made science possible is that the truth shall be told all the time. If we do not penalise false statements made in error, we open up the way, don't you see, for false statements by intention. And of course a false statement of fact made deliberately, is the most serious crime a scientist can commit."[3]

Not every scientist and technical professional buys this. Arguably, the most dangerous group of scientists are those who so strongly advocate a political or social agenda that sound science can be ignored or manipulated to advance certain causes. Green engineering is particularly vulnerable to such advocacy. We may believe so strongly in sustainability that we become selective in facts. For example, environmental science has sometimes been asked to accept the justification of using morally unacceptable means to achieve the greater good.[4] The journal *Conservation Biology* published a number of scientific, philosophical, and ethical perspectives as to whether to misuse science to promote the larger goal (conservation) to protect the black sea turtle. Even though the taxonomy is scientifically incorrect (i.e., the black sea turtle is not a unique species), some writers called for a *geopolitical taxonomy*.[5] The analogy of war has been invoked as a justification, with one writer even declaring that "it is acceptable to tell lies to deceive the enemy." The debate moderators asked a telling question: "Should legitimate scientific results then be withheld, modified, or 'spun' to serve conservation goals?" Continuing with the war analogy, some scientists likened the deceptive taxonomy to propaganda needed to prevent advances by the enemy. The problem is that, as Snow would put it, once you stop telling the truth, you have lost credibility as scientists, even if the deception is for a noble cause.[6] Two writers, Kristin Shrader-Frechette and Earl D. McCoy, emphasized that credible science requires that "in virtually all cases in professional ethics, the public has the right to know the truth when human or environmental welfare is at issue."[7]

The Green Categorical Imperative

The concept of sustainability has been embraced by many. It is, so to speak, a social virtue. The classical works of Aristotle, Aquinas, and Kant, among others, make the case for life being a mix of virtues and vices available to humans. Virtue can be defined as the power to do good or a habit of doing good. In fact, one of Aristotle's most memorable lines is that "excellence is habit." If we do good, we are more likely, according to Aristotle, to keep doing good. Conversely, vice is the power and habit of doing evil. The subjectivity or relational nature of good and evil, however, causes discomfort among engineers and design pofessionals. We place great import on certainty and consistency of definition.

Aristotle tried to clarify the dichotomy of good and evil by devising lists of virtues and vices, which amount to a taxonomy of good and evil. One of the many achievements of Aristotle was his keen insight as to the similarities of various kinds of living things. He categorized organisms into two kingdoms, plants and animals. Others no doubt made such observations, but Aristotle documented them. He formalized and systematized this taxonomy. Such a taxonomic perspective also found its way into Aristotle's moral philosophy.

Not too long ago, biological taxonomy held Aristotle's two-kingdom structure. However, the difficulty of placing microbes and other ambiguous organisms into one of these two kingdom led to the need for additional kingdoms. Ethics is arguably even more difficult to classify. We will not all agree on which of the virtues and vices are best or even whether something is a virtue or a vice (e.g., loyalty), but one concept does seem to come to the fore in most major religions and moral philosophies: empathy. Putting oneself in another's situation is a good metric for virtuous acts. The golden rule is at the heart of Immanuel Kant's categorical imperative, which states in clearer English than it was given at the beginning of the chapter: "Act only according to that maxim by which you can at the same time will that it should become a universal law."[8]

A simplified way to think about the categorical imperative is as follows: When deciding whether to act in a certain way, ask if your action (or inaction) will make for a better world if all others in your situation acted in the same way. An individual action's virtue or vice is seen in a comprehensive manner as a life cycle, if you will. It is not whether one should pour a few milligrams of a toxic substance down the drain; it is whether everyone with this amount of toxic substances should do likewise. The overall stewardship of the environment may cause one to rethink an action (as has been the case for decades now). A corollary to this concept is what Elizabeth Kiss, the former Director of Duke's Kenan Center for Ethics and now President of Agres Scott College, calls the "Six O'clock News" imperative. That is, when deciding whether an action is ethical or not, consider how your friends and family would feel if they heard all its details on tonight's TV news. That may cause one to consider more fully the possible externalities and consequences of one's decision.

The virtue of sustainability is a type of social justice. That is, we must do no harm now or in the future. This means that we must not only avoid hurting others by our actions, but we ought to safeguard the environment and the health of others in what we do and what we leave undone. Further complicating matters, biological systems, including very large ones such as biomes, consist of humans, nonhuman oganisms, and nonliving (abiotic) material. Stresses on any of these can affect the entire system.

Kant uses the categorical imperative maxim to underpin duty ethics (called *deontology*) with empathetic scrutiny. However, empathy is not the exclusive domain of duty ethics. In teleological ethics, sustainability is a palliative approach to deal with the problem of "ends justifying the means." Other philosophers also incorporated this viewpoint into their frameworks. In fact, John Stuart Mill's utilitarianism's axiom of "greatest good for the greatest number of people" is moderated by his harm principle, which, at its heart, is empathetic. That is, even though an act can be good for the majority, it may still be unethical if it causes undue harm to even one person. Sustainability is also embraced by contractarianism, as articulated by Thomas Hobbes as social contract theory. For example, John Rawls has moderated the social contract with the "veil of ignorance" as a way to consider the perspective of the weakest members of society, including those in the future. And if we add that others includes the nonhuman components, the weakest, most vulnerable parts of the planet need special protections.

The fundamental canons of the National Society of Professional Engineers (NSPE) code of ethics[9] captures what engineers "ought" to do. It states that engineers, in the fulfillment of their professional duties, must:

1. Hold paramount the safety, health, and welfare of the public.
2. Perform services only in areas of their competence.
3. Issue public statements only in an objective and truthful manner.
4. Act for each employer or client as faithful agents or trustees.
5. Avoid deceptive acts.
6. Conduct themselves honorably, responsibly, ethically, and lawfully so as to enhance the honor, reputation, and usefulness of the profession.

Let us consider each canon as it relates to sustainability. The canons are the professional equivalents of morality, which refers to societal norms about acceptable (virtuous/good) and unacceptable (evil/bad) conduct. These norms are shared by members of society to provide stability as determined by consensus.[10] Philosophers consider professional codes of ethics and their respective canons to be *normative ethics*, which is concerned with classifying actions as right and wrong without bias. Normative ethics is contrasted with *descriptive ethics*, which is what a group actually believes to be right and wrong and how it enforces conduct. Normative ethics regards ethics as a set of norms related to actions. Descriptive ethics deals with what "is" and normative ethics addresses "what should be."

The philosopher Bernard Gert categorizes behaviors into what he calls a *common morality*, which is a system that thoughtful people use implicitly to make moral judgments.[11] According to Gert, humans strive to avoid five basic harms: death, pain, disability, loss of freedom, and loss of pleasure. Arguably, the job of the designer is to design devices, structures, and systems that mitigate against such harms in society. Similarly, Gert identifies 10 rules of common morality:

1. Do not kill.
2. Do not cause pain.
3. Do not disable.
4. Do not deprive of freedom.
5. Do not deprive of pleasure.

6. Do not deceive.
7. Keep your promises.
8. Do not cheat.
9. Obey the law.
10. Do your duty.

Most of these rules are proscriptive. Only rules 7, 9, and 10 are prescriptive, telling us what to do rather than what not to do. The first five directly prohibit the infliction of harm on others. The next five lead indirectly to prevention of harm. Interestingly, these rules track quite closely with the tenets and canons of the engineering profession (see Table 6.1).

The Gert model is good news for green design. Numerous ethical theories can form the basis for engineering ethics and moral judgment. Again, Kant is known for defining ethics as a sense of *duty*. Hobbes presented ethics within the framework of a *social contract*, with elements reminiscent of Gert's common morality. Mill considered ethics with regard to the goodness of action or decision as the basis for *utilitarianism*. Philosophers and ethicists spend much effort and energy deciphering these and other theories as paradigms for ethical decision making. Engineers can learn much from these points of view, but in large measure, engineering ethics is an amalgam of various elements of many theories. As evidence, the American Society of Mechanical Engineers (ASME) has succinctly bracketed ethical behavior into three models[12]:

1. *Malpractice, or minimalist, model.* In some ways this is really not an ethical model in that the engineer is only acting in ways that are required to keep his or her license or professional membership. As such, it is more of a *legalistic* model. The engineer operating within this framework is concerned exclusively with adhering to standards and meeting requirements of the profession and any other applicable rules, laws, or codes. This is often a retroactive or backward-looking model, finding fault after failures, problems, or accidents happen. Any ethical breach is evaluated based on design, building, operation, or other engineering steps that have failed to meet recognized professional standards. This is a common approach in failure engineering and in ethical review board considerations. It is also the basis of numerous engineering case studies. As such, it is crucial to design professionalism in that it establishes clear baselines and criteria. However, true professionalism transcends the minimalist model.
2. *Reasonable-care, or due-care, model.* This model goes a step further than the minimalist model, calling on the engineer to take reasonable precautions and to provide care in the practice of the profession. Interestingly, every

Table 6.1 Canons of the National Society of Professional Engineers Compared to Gert's Rules of Morality

NSPE Code of Ethics	Most Closely Linked to Rules of Morality Identified by Gert
1. Hold paramount the safety, health, and welfare of the public.	• Do not kill. • Do not cause pain. • Do not disable. • Do not deprive of pleasure. • Do not deprive of freedom.
2. Perform services only in areas of their competence.	• Do not deceive. • Keep your promises. • Do not cheat. • Obey the law. • Do your duty.
3. Issue public statements only in an objective and truthful manner.	• Do not deceive.
4. Act for each employer or client as faithful agents or trustees.	• Do not deprive of pleasure. • Keep your promises. • Do not cheat. • Do your duty.
5. Avoid deceptive acts.	• Do not deceive. • Keep your promises. • Do not cheat.
6. Conduct yourselves honorably, responsibly, ethically, and lawfully so as to enhance the honor, reputation, and usefulness of the profession.	• Do your duty. • Obey the law. • Keep your promises.

major philosophical theory of ethics includes such a provision, such as the harm principle in utilitarianism, the veil of ignorance in social contract ethics, and the categorical imperative in duty ethics. It also applies a legal mechanism, known as the *reasonable person standard*. Right or wrong is determined by whether the design professional's action would be seen as ethical or unethical according to a "standard of reasonableness as seen by a normal, prudent nonprofessional."[13]

3. *Good works model*. A truly ethical model goes beyond abiding by the law or preventing harm. An ethical design professional excels beyond the standards and codes and does the right thing to improve product safety, public health, or social welfare. An analytical tool related to this model is the *net goodness model,* which estimates the goodness or wrongness of an action by weighing its morality, likelihood, and importance.

This model is rooted in moral development theories such as those expounded by Kohlberg,[14] Piaget,[15] and Rest,[16] who noted that moral action is a complex process entailing four components: moral awareness (or sensitivity), moral judgment, moral motivation, and moral character. The actor must first be aware that the situation is moral in nature; that is, at least that the actions considered would have consequences for others. Second, the actor must have the ability to judge which of the potential actions would yield the best outcome, giving consideration to those likely to be affected. Third, the actor must be motivated to prioritize moral values above other sorts of values, such as wealth or power. Fourth, the actor must have the strength of character to follow through on a decision to act morally.

Piaget, Kohlberg, and others (e.g., Duska and Whelan[17]) have noted that the two most important factors in determining a person's likelihood of behaving morally—that is, of being morally aware, making moral judgments, prioritizing moral values, and following through on moral decisions—are age and education. Applied to professional ethics, age may better translate to time (experience) in the design field. Experience[18] seems to be particularly critical regarding moral judgment: A person's ability to make moral judgments tends to grow with maturity as he or she pursues further education, generally reaching its final and highest stage of development in early adulthood. This is analogous to professional, continuing education and experiences. A general theory of moral development is illustrated in Table 6.2.

Kohlberg insisted that these steps are progressive. He noted that in the two earliest stages of moral development, which he combined under the heading "preconventional level," a person is motivated primarily by the desire to seek pleasure and avoid pain. The conventional level consists of stages 3 and 4: In stage 3 the consequences that actions have for peers and their feelings about these actions; in stage 4, considering how the wider community will view the actions and be affected by them. Few people reach the postconventional stage, wherein they have an even broader perspective: Their moral decision making is guided by universal moral principles[19]: that is, by principles that reasonable people would agree should bind the actions of all people who find themselves in similar situations.

A normative model of green engineering can be developed along the same lines. The moral need to consider the impact that one's actions will have on

Table 6.2 Kohlberg's Stages of Moral Development

Preconventional level	1. Punishment–obedience orientation
	2. Personal reward orientation
Conventional level	3. "Good boy"–"nice girl" orientation
	4. Law and order orientation
Postconventional level	5. Social contract orientation
	6. Universal ethical principle orientation

Source: L. Kohlberg, *The Philosophy of Moral Development*, Vol. 1, Harper & Row, San Francisco, CA, 1981.

others forms the basis for the normative model we are proposing. Pursuing an activity with the goal of obeying the law has as its driving force the avoidance of punishment, and pursuing an activity with the goal of improving profitability is a goal clearly in line with stockholders' desires; presumably customers', suppliers', and employees' desires must also be met at some level. Finally, pursuing an activity with the goal of "doing the right thing," behaving in a way that is morally right and just, can be the highest level of engineering behavior. This normative model of ethical design and engineering is illustrated in Figure 6.2.

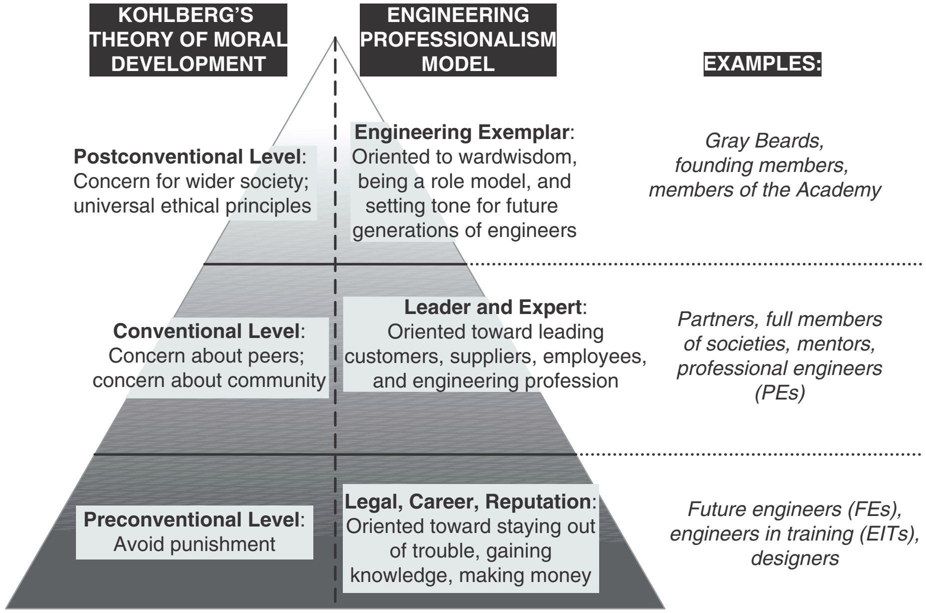

Figure 6.2 Comparison of Kohlberg's moral development stages to professional development in engineering.

From: D. Vallero, 2007, *Biomedical Ethics for Engineers*, Academic Press, Burlington, MA.

There is a striking similarity between Kohlberg's model of moral development and the model of professional growth in design fields. Avoiding punishment in the moral development model is similar to the need to avoid problems early in one's career. The preconventional level and early career experiences have similar driving forces.

At the second level in the moral development model is a concern with peers and community; in the professionalism model the engineer and architect must balance the needs of clients and fellow professionals with those of society at large. Design services and products must be of high quality and be profitable, but the focus is shifting away from self-centeredness and personal well-being toward external goals.

Finally, at the highest level of moral development a concern with universal moral principles begins to govern actions; in the corporate model, fundamental moral principles relate more to professionalism than to corporate decisions. The driving force or motivation is trying to do the right thing on a moral (not legal or financial) basis. These behaviors set the example for the entire profession, now and in the future.

Professional growth is enhanced when designers and technical managers base their decisions on sound business and engineering principles. Ethical content is never an afterthought but is integrated within the business and design decision-making process. That is, the design exemplars recognize the broad impacts that their decisions may have, and they act such that their actions will be in the best interest not only of themselves and the organization they represent, but also of the broader society and even future generations.

Much of ethics training in the design fields to date has emphasized preconventional thinking: that is, adherence to codes, laws, and regulations within the milieu of profitability for the organization. This benefits the designer and organization but is only a step toward full professionalism, the type needed to confront sustainability challenges. We who teach professional ethics must stay focused on the engineer's principal client, "the public." The engineer, architect, and other design professionals must navigate their professional codes. The NSPE code, for example, reminds its members that "public health and welfare are paramount considerations."[20] Public safety and health, considerations affect the design process directly. By definition, if engineers must "hold paramount" the safety, health, and welfare of the public, this mandate has primacy over all the others delineated in the code. So anything the professional engineer does cannot violate this canon. No matter how competent, objective, honest, and faithful, the engineer must not jeopardize public safety, health, or welfare. This is a challenge for such a results-oriented profession, but it is a motivation to be green.

Almost every design now requires at least some attention to sustainability and environmental impacts. As evidence, we discussed in the previous chapter, the recent changes in drug delivery the move away from the use of greenhouse gas propellants such as chlorofluorocarbons (CFCs) and instead using pressure differential systems (such as physical pumps) to deliver medicines illustrates the green view in the public's interest. This may seem like a small thing or even a nuisance to those who have to use them, but it reflects an appreciation for the importance of incremental effects.

Recalling Kant, one inhaler does little to affect the ozone layer or threaten the global climate, but millions of inhalers can produce sufficient halogenated and other compounds that the threat must be considered in designing medical devices. To the best of our abilities, we must ensure that what we design is sustainable over its useful lifetime. This requires that the designer think about the life cycle not only during use, but when the use is complete. Such programs as design for recycling and design for disassembly allow the engineer to consider the consequences of various design options in space and time. They also help designers to pilot new systems and to consider scale effects when ramping up to full production of devices.

Like virtually everything else in design, best service to the public is a matter of optimization. The variables that we choose to give large weights will often drive the design. Designing structures, products, and systems in a sustainable manner is a noble and necessary end. The engineer must continue to advance the state of the science in high-priority areas. Any possible adverse effects must be recognized. These should be incorporated and weighted properly when we optimize benefits. We must weigh these benefits against possible hazards and societal costs. Unfortunately, many of the green benefits do not easily lend themselves to monetary value.

ENVIRONMENTAL JUSTICE

Environmental policies have not always been in lockstep with justice. In fact, environmental causes have too often been in direct opposition to social justice. Green design objectives must always be viewed within the context of fairness. To paraphrase the harm principle, even if a project is very green, it may not be sustainable if certain segments of society suffer inordinate hazards and risks. Examples include the use of environmental impact assessments to stop affordable housing projects and decisions to site an unpopular facility, such as a landfill, factory, or power plant, in a manner that garners the least complaints. At first glance, such decisions appear to be sound means of selecting a site. However, these types of decisions frequently have been the result of heeding those with the loudest voices and the most potent political and economic power at the expense of those not so endowed. This type of institutional injustice brings about an inordinate burden of pollution on the poorer neighborhoods and communities.

Thus, to move toward green objectives, we must have a thorough grasp of justice. Justice is a universal human value. It is a concept that is built into every code of practice and behavior, including the codes of ethics of all engineering and other design disciplines. Justice is the linchpin of social responsibility. The United States' Declaration of Independence states:

> We hold these truths to be self-evident, that all men are created equal, that they are endowed by their Creator with certain unalienable Rights, that among these are Life, Liberty and the pursuit of Happiness. . . . That whenever any Form of Government becomes destructive of these ends, it is the Right of the People to alter or to abolish it, and to institute new Government, laying its foundation on such principles and organizing its powers in such form, as to them shall seem most likely to effect their Safety and Happiness.

These unalienable rights of life, liberty, and the pursuit of happiness depend on a livable environment. The Declaration warns against a destructive government. Arguably, the government holds a central role of overcoming the forces that will militate against equity in environmental protection. Democracy and freedom are at the core of achieving fairness, and we Americans rightfully take great pride in these foundations of our republic.

By extension, the "equal protection" clause in the Constitution also sets the stage for environmental justice:

> All persons born or naturalized in the United States, and subject to the jurisdiction thereof, are citizens of the United States and of the state wherein they reside. No state shall make or enforce any law which shall abridge the privileges or immunities of citizens of the United States; nor shall any state deprive any person of life, liberty, or property, without due process of law; nor deny to any person within its jurisdiction the equal protection of the laws.

The framers of our Constitution wanted to make sure that life, liberty, and the pursuit of happiness were available to all. This begins with the protection of property rights and is extended, with the Bill of Rights, to human and civil rights to all the people. Theologian Reinhold Neibuhr contended that justice is something that requires work: "Man's capacity for justice makes democracy possible, but man's inclination to injustice makes democracy necessary."[21] The reality articulated by Neibuhr indicates the complexities and failings of the human condition, and the vigilance and hard work required to provide a public benefit such as an environment that supports public health and ecosystems. Certainly, a modern connotation of "safety and happiness" is that of risk reduction. Thus, the socially responsible designer is an agent of justice. What has become evident only in the past few decades is that without a clean environment, life is threatened by toxic substances, liberty is threatened by the loss of resources, and happiness is less likely in an unhealthful and unappealing place to live. Thus, sustainability and justice go hand in hand.

Justice must be universal applied fairly to everyone. One of the few things that everyone shares is the environment. We breathe from the air in the same troposphere. All of our water circulates through the hydrological cycle. Our food stores the solar energy from the same sun. Our products are derived from the same Earth's crust. But within this environment, few things are distributed evenly in terms of amount and quality. Some breathe cleaner air than others, drink purer water than most, eat food that is less contaminated than that available to the majority of the world's inhabitants, and have better tools and toys than everyone else.

Since the distribution of goods and services is so uneven, we may be tempted to assume that systems are fair simply because "most" are satisfied with the current situation. However, the only way to protect public health and the environment is to ensure that *all* persons are adequately protected. In the words of Reverend Martin Luther King, "Injustice anywhere is a threat to justice everywhere."[22] By extension, if any group is disparately exposed to an unhealthy environment, the entire nation is subjected to inequity and injustice. Put in a more positive way, we can work to provide a safe and livable environment by including everyone, leaving no one behind. This mandate has a name, *environmental justice*, and green design is a tool that extends equal protection to matters of public health and environmental quality.

The concept of environmental justice has evolved over time. In the early 1980s, the first name for the movement was *environmental racism*, followed by *environmental equity.* These transitional definitions reflect more than changes in jargon. When attention began to be paid to the particular incidents of racism, the focus was logically placed on eradicating the menace at hand (i.e., blatant acts of willful racism). This was a necessary, but not completely sufficient component in addressing the environmental problems of minority communities and economically disadvantaged neighborhoods, so the concept of equity was employed more assertively. Equity implies the need not only to eliminate the overt problems associated with racism, but to initiate positive change to achieve more evenly distributed environmental protection.

Sidebar: Applying the Synthovation/Regenerative Model: Social Justice

Environmental justice is best achieved when fairness is a consideration early in the design process. Siting unpopular facilities such as landfills and heavy industrial centers near poorer and minority neighborhoods has been "easier" in lower-income and minority neighborhoods. However, if an integrated design approach is applied, potential problems such as that of unfairness can be avoided. In this case, another voice can be added to those of the designers, technical professionals, and builders. Stakeholders, present and future, can share information and the history of an area that may not be readily available, if available at all, through the usual documentation. For example, many southeastern U.S. communities have rich histories that have only been captured by oral traditions. By giving these stakeholders a place at the drawing table, future problems can be avoided and rich cultural resources can be optimized. Historic and cultural preservation can be built into the process. Even sources of pollution, such as the location of buried wastes, can be identified by residents who are well aware of previous industries and land uses.

We now use the term *environmental justice,* which is usually applied to social issues, especially as they relate to neighborhoods and communities. The *environmental justice* (EJ) *communities* possess two basic characteristics:

1. They have experienced historical (usually multigenerational) exposures to disproportionately[23] high doses of potentially harmful substances (the *environmental* part of the definition). These communities are home to numerous pollution sources, including heavy industry and pollution control facilities, which may be obvious by their stacks and outfall structures, or which may be more subtle, such as long buried wastes with little evidence on the surface of their existence. These sites increase the likelihood of exposure to dangerous substances. Exposure is preferred to *risk*, since risk is a function of the hazard and the exposure to that hazard. Even a substance with very high toxicity (one type of hazard) that is confined to a laboratory of a manufacturing operation may not pose much of a risk, due to the potentially low levels of exposure.
2. Environmental justice communities have certain specified socioeconomic and demographic characteristics. EJ communities must have a majority representation people of low socioeconomic status, or those who are racially, ethnically, and historically disadvantaged (the *justice* part of the definition).

These definitions point to the importance of an integrated response to ensure justice. The first component of this response is a sound scientific and engineering underpinning to decisions. The technical quality of designs and operations is vital to addressing the needs of any group. However, the engineering codes' call that we be "faithful agents" lends an added element of social responsibility to green design.[24] For example, we cannot assume a "blank slate" for any design.

Historic disenfranchisement and even outright bias may well have put certain neighborhoods at a disadvantage.

Thus, the responsibility of professionals cannot stop at sound science but should consider the social milieu, especially possible disproportionate impacts. The determination of disproportionate impacts, especially pollution-related diseases and other health endpoints, is a fundamental step in ensuring environmental justice. But even this step relies on the application of sound physical science. Like everything else that design professionals do, we must first assess the situation to determine what needs to be done to improve it. As a first step in assessing environmental insult, epidemiologists look at clusters and other indications of elevated exposures and effects in populations. For example, certain cancers, as well as neurological, hormonal, and other chronic diseases, have been found to be significantly higher in minority communities and in socioeconomically depressed areas. Acute diseases may also be higher in certain segments of society, such as pesticide poisoning in migrant workers.[25] These are examples of *disparate effects.* In addition, each person responds to an environmental insult uniquely and that person is affected differently at various life stages. For example, young children are at higher risk than adults following exposure to neurotoxins. This is an example of *disparate susceptibility.* However, subpopulations can respond differently than the entire population, meaning that genetic differences seem to affect people's susceptibility to contaminant exposure. Scientists are very interested in genetic variation, so that genomic techniques[26] (e.g., identifying certain polymorphisms) are a growing area of inquiry.

In a sense, historical characteristics constitute the "environmental" aspects of EJ communities, and socioeconomic characteristics entail the "justice" considerations. The two sets of criteria are mutually inclusive, so for a community to be defined as an EJ community, both of these sets of criteria must be present.

A recent report by the Institute of Medicine[27] found that numerous EJ communities experience a "certain type of double jeopardy." The communities must endure elevated levels of exposure to contaminants while being ill equipped to deal with these exposures, because so little is known about the exposure scenarios in EJ communities. The first problem (i.e., higher concentrations of contaminants) is an example of *disparate exposure.* The latter problem is exacerbated by the disenfranchisement from the political process that is endemic to EJ community members. This is a problem of *disparate opportunity* or even *disparate protection.*[28] The report also found large variability among communities as to the type and amount of exposure to toxic substances. Each contaminant has its own type of toxicity. For example, one of the most common exposures in EJ communities is to the metal lead and its compounds. The major health problem associated with lead is central and peripheral nervous system diseases, including learning and behavioral problems. Another common contaminant in EJ communities is benzene, as well as other organic solvents. These contaminants can also be neurotoxic, but also have toxicity profiles very different from those of neurotoxic metals such as lead. For example, benzene is a potent carcinogen, having been linked to leukemia and lymphatic tumors as well as to severe types of anemia. They also have very different exposure profiles. For example, lead exposure often takes place in the home and yard, whereas benzene exposures often result from breathing air near a source (e.g., at work or near an industry, such as an oil refinery or pesticide manufacturer). The Institute's findings point to the need for improved approaches for characterizing human exposures to toxicants in EJ communities. Numerous communities have experienced uneven, and arguably unjust, disparities in environmental protection. However, there is little consensus as to what defines an environmental injustice and whether, in fact, an injustice has occurred in many of these communities.

Environmental Impact Statements and the Complaint Paradigm

In most modern settings, environmental response is often precipitated first by a complaint. This is problematic in that its underlying assumption of fairness is that everyone not only has a voice in the process, but that that voice is loud enough to be heard. If a certain group of people has had little or no voice in the past, they are likely to feel, and to be, disenfranchised. Although there have been recent examples to the contrary, African-American communities have had little success in voicing concerns about environmentally unacceptable conditions in their neighborhoods. Hispanic-Americans may have even less voice in environmental matters since their perception of government, the final arbiter in many environmental disagreements, is one of skepticism and outright fear of reprisal in the form of being deported or being "profiled." Many of the most adversely affected communities are not likely to complain.

Sidebar: Applying the Synthovation/Regenerative Model: Environmental Management Systems

Complaints are a poor metric for ensuring a design's success. By the time the client and the public share their displeasure, mistakes have already been made. Unfortunately, many of the tools for environmental assessment have been post hoc. The transitional design process has embraced proactive tools, such as the environmental audit and managements systems. Environmental management systems (EMSs) help enterprises plan and organize interactions with the environment, especially in regard to human health, resource use, and environmental contamination. The most recognizable EMS is the international standard, ISO 14001, which is being applied with some regularity in many countries. The ISO 14001 approach is much like the integrated approaches discussed in this book*:

1. Establishing an environmental policy that encourages systematic solutions
2. Reviewing actual and potential environmental outcomes from the enterprise's operations
3. Setting goals
4. Preparing and implementing plans to achieve these goals
5. Monitoring the progress toward these goals
6. Reporting
7. Continuously improving and feeding back to the earlier steps

It appears that EMSs are designed to be integrated and systematic. They are means of finding ways to prevent problems and of seeking better ways of getting results.

*N. P. Cheremisinoff and A. Bendavid-Val, *Green Profits: The Manager's Handbook for ISO 14001 and Pollution Prevention*, Butterworth-Heinemann, Burlington, MA, 2001.

Harkening back to Aldo Leopold's land ethic, we are reminded that the use of land is dependent on the values placed on it. The incremental effects of a number of highly visible environmental insults along with myriad small ones that are not very noticeable in their own right, have changed the landscape of environmental awareness. Public projects such as dams and highways have caused incremental but dramatic changes in the environment. With the growing awareness the public demand for environmental safeguards and remedies for environmental problems encouraged an expectation of a greater role for government. A number of laws were on the books prior to the 1960s, such as early versions of federal legislation to address limited types of water and air pollution, and some solid waste issues, such as the need to eliminate open dumping. In fact, key legislation to protect waterways and riparian ecosystems was written at the end of the nineteenth century in the form of the Rivers and Harbors Act (the law that set the stage for the U.S. Army Corps of Engineers to permit proper dredging operations, later enhanced by Section 404 of the Clean Water Act).

The real growth, however, followed the tumultuous decade of the 1960s. Care for the environment had become a social cause, akin to the civil rights and anti-war movements. Major public demonstrations on the need to protect "Spaceship Earth" encouraged elected officials to address environmental problems, exemplified by air pollution "inversions" that capped polluted air in urban valleys, leading to acute diseases and increased mortality from inhalation hazards, the "death" of the Erie Canal, and rivers catching on fire in Ohio and Oregon.

The environmental movement was institutionalized in the United States by a series of new laws and legislative amendments. The National Environmental Policy Act (NEPA) was in many ways symbolic of the new federal commitment to environmental stewardship. It was signed into law in 1970 after contentious hearings in the U.S. Congress. NEPA was not really a technical law. It did two main things: created the Environmental Impact Statement (EIS) and established the Council on Environmental Quality (CEQ) in the Office of the President. Of the two, the EIS represented a sea change in how the federal government was to conduct business. Agencies were required to prepare EISs on any major action that they were considering that could "significantly" affect the quality of the environment. From the outset, the agencies had to reconcile often-competing values: their mission and the protection of the environment.

The CEQ was charged with developing guidance for all federal agencies on NEPA compliance, especially when and how to prepare an EIS. The EIS process combines scientific assessment with public review. The process is similar for most federal agencies. The National Aeronautics and Space Administration (NASA) decision flowchart is shown in Figure 6.3. Local and state governments have adopted similar requirements for their projects (e.g., the North Carolina process is shown in Table 6.3). Agencies often strive to receive a FONSI[29] (finding of no significant impact), so that they may proceed unencumbered on a mission-oriented project.[30] The Federal Highway Administration's FONSI process (see Fig. 6.4) provides an example of the steps needed to obtain a FONSI for a project.

Whether a project either leads to a full EIS or a waiver through the FONSI process, it will have to undergo an evaluation. This step is referred to as an *environmental assessment*. An incomplete or inadequate assessment will lead to delays and increases the chance of an unsuccessful project, so sound science and community input are needed from the outset of the project design.

The final step in the federal process is the record of decision (ROD), which describes the alternatives and the rationale for final selection of the best alternative. It also summarizes the comments received during public reviews and how the comments were addressed. Many states have adopted similar requirements for their RODs.

The EIS documents were to provide full disclosure of actual or possible problems if a federal project is carried out. This was accomplished by looking at all of the potential impacts to the environmental from any of the proposed alternatives, and comparing those outcomes to a "no action" alternative. At first, many agencies tried to demonstrate that their "business as usual" was in fact very environmentally sound. In other words, the environment would be better off with the project than without it (action is better than no action). Too, often, however, an EIS was written to justify the agency's mission-oriented project. One of the

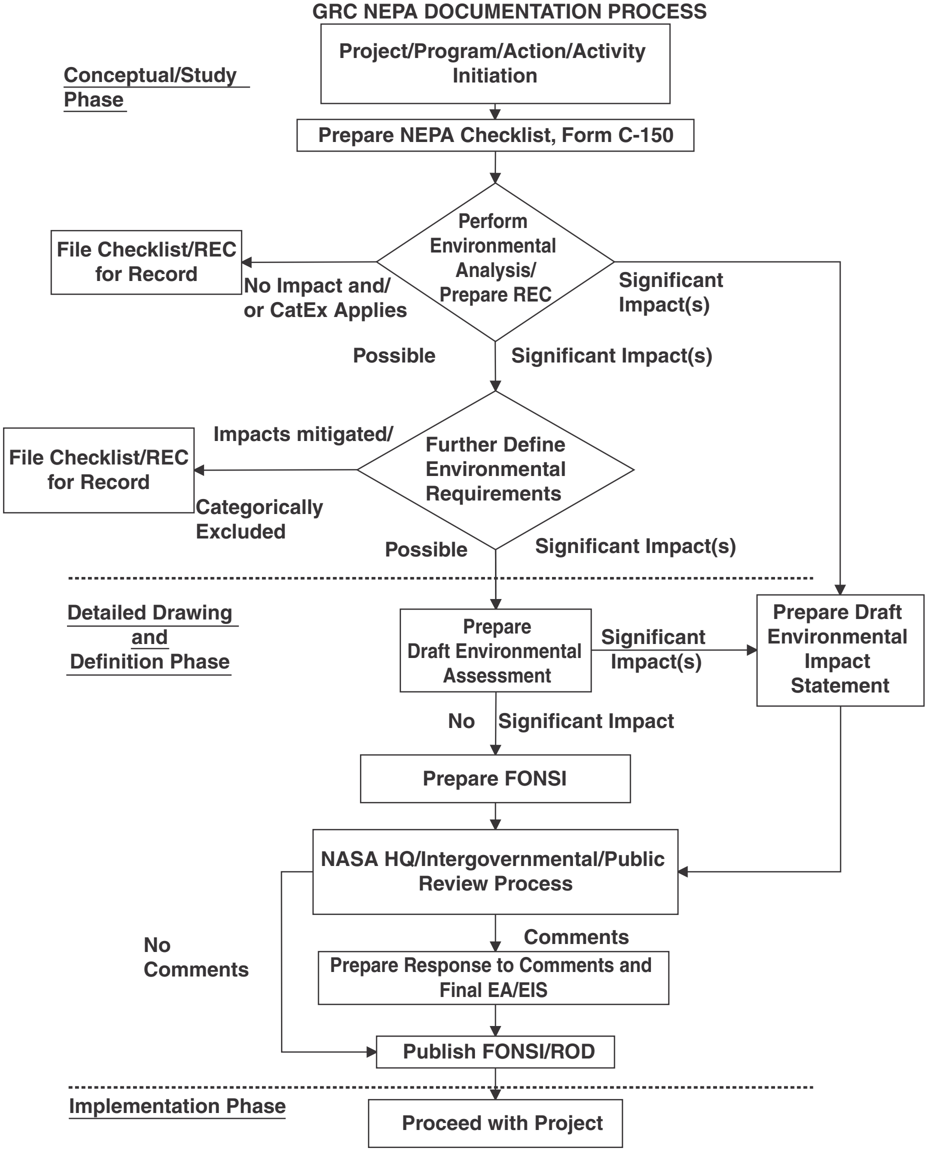

Figure 6.3 Decision flowchart for environmental impact statements at the National Aeronautics and Space Administration.

key advocates for the need for a national environmental policy, Lynton Caldwell, is said to have referred to this as the federal agencies using EIS to "make an environmental silk purse from a mission-oriented sow's ear!"[31]

The courts have ruled clearly and strongly that federal agencies must take NEPA seriously. Some of the aspects of the "give and take" and evolution of federal agencies' growing commitment to environmental protection were the acceptance of the need for sound science in assessing environmental conditions

Table 6.3 North Carolina's State Environmental Policy Act (SEPA) Review Process

Step I: An applicant consults/meets with the Department of Environmental and Natural Resources (DENR) about the potential need for SEPA document and to identify/scope issues of concern.
Step II: The applicant submits a draft environmental document to the DENR.
- The environmental document is either an environmental assessment (EA) or an environmental impact statement (EIS).

Step III: The DENR–lead division reviews the environmental document.
Step IV: The DENR–other divisions review the environmental document.
- 15 to 25 calendar days.
- DENR issues must be resolved prior to sending to the Department of Administration–State Clearinghouse (SCH) review.

Step V: The DENR–lead division sends the environmental document and FONSI? to the SCH.
Step VI: SCH publishes a notice of availability for an environmental document in the NC *Environmental Bulletin*. Copies of the environmental document and FONSI? are sent for comments to the appropriate state agencies and regional clearinghouses.
- Interested parties have either 30 (EA) or 45 (EIS) calendar days from the bulletin publication date to provide comments.

Step VII: The SCH forwards copies of the environmental document comments to the DENR–lead division which ensures that the applicant addresses the comments.
- The SCH reviews the applicant's responses to the comments and recommends whether or not the environmental document is adequate to meet SEPA requirements.
- Substantial comments may cause the applicant to submit a revised environmental document to the DENR–lead division. This will result in repeating steps III to VI.

Step VIII: The applicant submits a final environmental document to the DENR–lead division.
Step IX: The DENR–lead division sends the final environmental document and FONSI (in the case of EA and if not previously prepared) to the SCH.

Environmental Assessment

Step X: The SCH provides a letter stating one of the following:
- The document needs supplemental information
- document does not satisfy a FONSI and an EIS should be prepared
- document is adequate; the SEPA review is complete.

Environmental Impact Statement

Step XI: After the lead agency determines that the federal EIS is adequate, the SCH publishes an ROD in the NC *Environmental Bulletin*.

Notes:

Public hearing(s) are recommended (but not required) during the draft stage of document preparation for both EA *and* EIS. For an EA, if no significant environmental impacts are predicted, the lead agency (or sometimes the applicant) will submit both the EA and the FONSI to the SCH for review (either early or later in the process).

Finding of No Significant Impact: statement prepared by the lead division which states that the project proposed will have only minimal impact on the environment

and possible impacts, and the very large role of the public in deciding on the environmental worth of a highway, airport, dam, waterworks, treatment plant, or any other major project sponsored or regulated by the federal government. This has been a major impetus in the growth of the environmental disciplines since the 1970s. We needed experts who could not only "do the science" but who could communicate what their science means to the public (and we still do!).

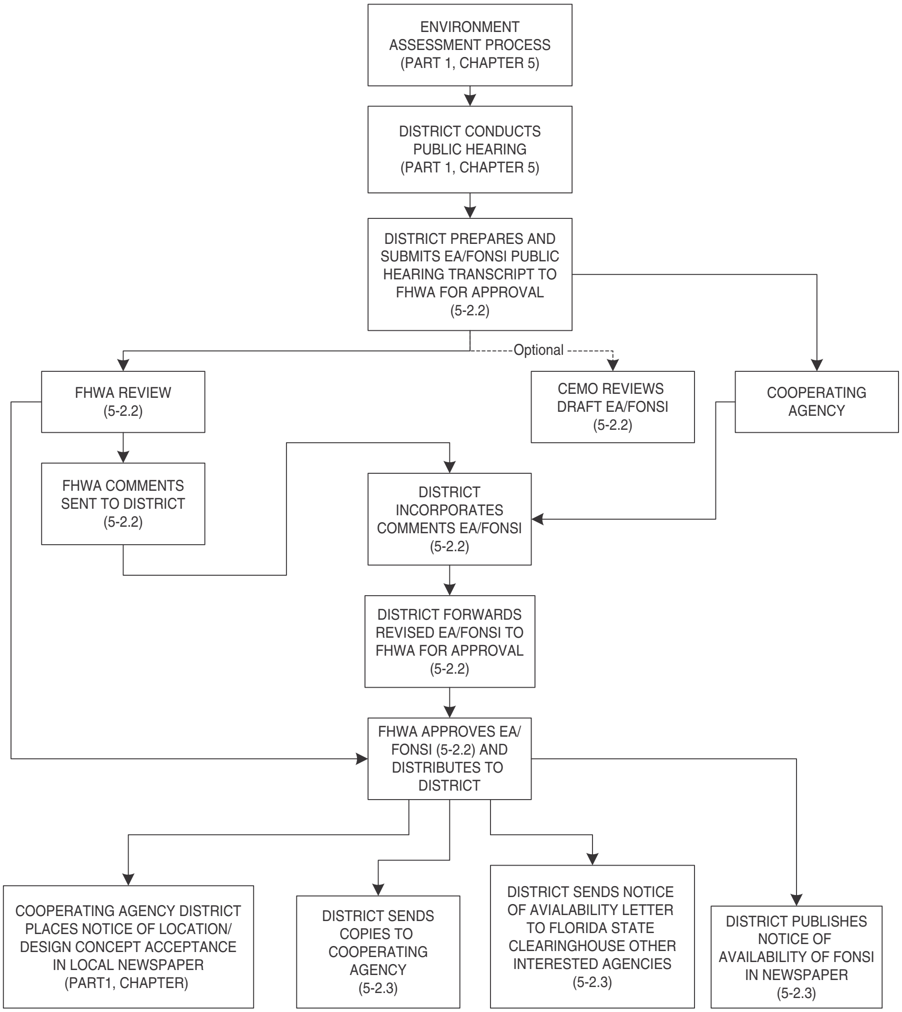

Figure 6.4 Decision flowchart for a finding of no significant impact for Federal Highway Administration projects.

From: Federal Highway Administration, “Guidance for preparing and processing environmental and Section 4(f) documents,” Technical Advisory T6640.8A, FHWA, Washington, DC, 1987.

Since NEPA’s passage, land-use decisions in the United States have had to follow from an environmental assessment. However, justice issues are not necessarily part of these assessments. Most environmental impact assessment handbooks prior to the late 1990s contained little information and few guidelines related to fairness issues in terms of housing and development. They were usually concerned about open space, wetland and farmland preservation, housing density, ratios of single- to multiple-family residences, owner-occupied housing versus rental housing, building height, signage and other aesthetic restrictions, land designated for public facilities such as landfills and treatment works, and institutional land uses for religious, health care, police, and fire protection. Whereas, those guidelines certainly have enhanced the livability of neighborhoods, they have also led to injustices.

When land uses change (usually to become more urbanized), the environmental impacts may be direct or indirect. Examples of direct land-use effects include *eminent domain,* which allows land to be taken with just compensation for the public good. Easements are another direct form of land-use impacts, such as a 100-m right-of-way for a highway project that converts any existing land use (e.g., farming, housing, or commercial enterprises) to a transportation use. Land-use change may also come about indirectly, such as the secondary effects of a project, which extend, in time and space, the influence of a project. For example, a wastewater treatment plant and its connected sewer lines will create accessibility that spawns suburban growth.[32] People living in very expensive homes may not even realize that their building lots were once farmland or open space and that had it not been for some expenditure of public funds and the use of public powers such as eminent domain, there would be no subdivision.

Environmentalists are generally concerned about increased population densities with the concomitant stresses on habitats, but housing advocates may be concerned that once the land use has been changed, environmental and zoning regulations may work against affordable housing. Even worse, environmental protection can be used as an excuse for some elitist and exclusionary decisions. In the name of environmental protection, whole classes of people are economically restricted from living in certain areas. This problem first appeared in the United States in the 1960s and 1970s in a search for ways to preserve open spaces and green areas. One measure was the minimum lot size. The idea was that rather than having the public sector securing land through easements or outright purchases (i.e., fee simple) to preserve open spaces, developers could either set aside open areas or require large lots in order to have their subdivisions approved. Thus, green areas would exist without the requisite costs and operation and maintenance entailed in public parks and recreational areas. Such areas have numerous environmental benefits, such as wetland protection, flood management, and aesthetic appeal. However, minimum lot size translates into higher costs for residences. The local rules for large lots that result in less affordable housing is called *exclusionary zoning*. One value (open space and green areas) is pitted against another (affordable housing). In some cases, it could be argued that preserving open spaces is simply a tool for excluding people of lesser means or even people of minority races.[33]

Land-use plans must reflect the fact that most of us want to protect the quality of our neighborhoods, but at the same time, designers and planners must take great care that their ends (environmental protection) are not used as a rationale for unjust means (unfair development practices). Like zoning ordinances and subdivision regulations, environmental laws and policies should not be used as a means to keep lower socioeconomic groups out of privileged neighborhoods. Thus, fairness must be an integral component of green design.

Sidebar: Applying the Synthovation/Regenerative Model: The War on Sediment

Properly developing a building site requires that attention be given to what leaves the site. Local subdivision regulations and codes generally require that systems be deployed to collect soil and other particles that can be carried away by moving water. The faster that water moves, the more energy it gains, and the greater the load of sediment that it can carry. Conversely, when water slows down, it begins to deposit this sediment load. Of course, since water flows downhill, its load of sediment travels to lower elevations. Surface water is impounded in depressions such as lakes and ponds. Thus, such depressions are the site of much of the runoff's deposition of its load.

Not only is the sediment itself a problem since it reduces the volume of the water body when the particles displace that available for water, but it also makes the water murkier (i.e., increases the turbidity). In addition, it changes the chemistry, since metals and organic compounds are sorbed to the individual particles or because the water is dissolving chemicals, like nutrients, along its pathway.

A good and green design needs to make use of the principles of gravity and carrying capacity of the moving water. An integrated design solution should also incorporate biology. Thus, one of the most effective and aesthetically pleasing options is the bioretention system (see Fig. S.6.1). This combines physical removal, such as gravity systems that allow the heavier particles to

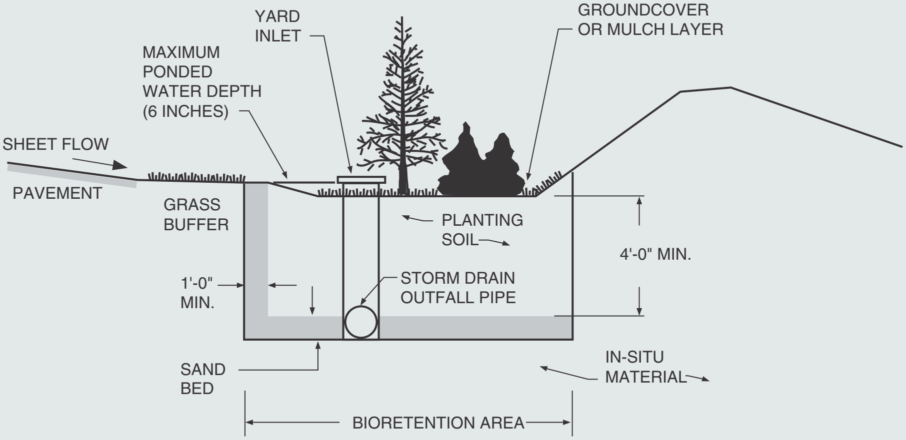

Figure S6.1 Bioretention system.

settle as the sheet flow enters the impounded water before reaching the yard inlet. Once the water and the sediment arrive, physical and biological processes go to work on the chemical compounds: filtering (sand beds and soil), sorbing (roots, soil, mulch, and ground cover), and transpiring (larger plants). These processes are complemented by microbial decomposition on and under the soil surface, along with nutrient removal that occurs in the root zone of diverse plant life. These processes act together to improve water quality.

Source: The principal source for this discussion and the source of the figure is the U.S. Environmental Protection Agency, "The greening curve: lessons learned in the design of the new EPA campus in North Carolina." EPA 220/K-02/001, 2001.

Environmental quality continues to be used, knowingly or innocently, to work against fairness: Ironically, people who are likely to be exposed to the hazards brought about by land-use decisions often do not participate in identifying and selecting options before land-use decisions are made. This is a type of "vexation without representation." In fact, since everything designers do may have an impact on health, safety, and welfare, inclusiveness should be standard operating procedure for all designs that potentially affect the public. Green design professionals can help continue to raise their client's appreciation of fairness and justice, as well as the improvement in the "bottom line" that can result from strong environmental programs. Sustainable design is gaining ground, so that professionals are called upon less to "sell" green programs, and more to provide reasonable and integrated design options. We simply must be attentive that even green plans can be unfair.

It is incorrect to conclude that the only way that environmental injustice occurs is financial. Certainly, ample cases can be found where the profit motive and its driving corporate decisions have driven the choice to site environmentally hazardous facilities where people are less likely to complain. However, public decisions have also brought lower socioeconomic communities into environmental harms way. Although public agencies such as housing authorities and public works administrations do not have a profit motive per se, they do need to address budgetary and policy considerations. If open space is cheaper and certain neighborhoods are less likely to complain (or by extension, vote against elected officials), the "default" for unpopular facilities such as landfills and hazardous waste sites may be to locate them in lower-income neighborhoods where they are less likely to attract attention. Elected and appointed officials and bureaucrats may be more likely to site other types of unpopular projects, such as public housing projects, in areas where complaints are less likely to be put forth or where land is cheaper.

Case Study: West Dallas Lead Smelter

In 1954, the Dallas, Texas, Housing Authority built a large public housing project on land immediately adjacent to a lead smelter. The project had 3500 living units and became a predominantly African-American community. During the 1960s the lead smelter stacks emitted over 200 tons of lead into the air annually. Recycling companies had owned and operated the smelter to recover lead from as many as 10,000 car batteries per day. The lead emissions were associated with blood lead levels in the housing project's children, and these were 35% higher than in children from comparable areas.

Lead is a particularly insidious pollutant because it can result in developmental damage. Study after study showed that the children at this project were in danger of higher lead levels, but nothing was done for over 20 years. Finally, in the early 1980s, the city brought suit against the lead smelter, and the smelter immediately initiated control measures that reduced its emissions to allowable standards. The smelter also agreed to clean up the contaminated soil around the smelter and to pay compensation to people who had been harmed.

This case illustrates two issues of environmental racism and injustice. First, the housing units should never have been built next to a potentially hazardous source, in this instance a lead smelter. The reason for locating the units there might have been justified on the basis of economics. The land was inexpensive and this saved the government money. The second issue is timing and timeliness. The foot dragging by the city in insisting that the smelter clean up the emissions created a type of inertia that was increasingly difficult to overcome. Once the case had been made, within two years the plant was in compliance. By 2003, blood lead levels in West Dallas were below the national average. Why did it take 20 years for the city to do the right thing?

Sources: D. E. Newton, *Environmental Justice,* Oxford University Press, New York, 1996 and Personal conversation with P. Aarne Vesilind.

Despite the general advances in environmental protection in the United States, the achievements have not been evenly disseminated throughout our history environmental science and engineering. Like most aspects of our culture for the past three centuries, has not been completely just and fair. The history of environmental contamination teems with examples in which certain segments of society have been exposed inordinately to chemical hazards. This has been particularly problematic for communities of low socioeconomic status. For example, the landmark study by the Commission for Racial Justice of the United Church of Christ[34] found that the rate of landfill siting and the presence of hazardous sites in a community were disproportionately higher in African-American

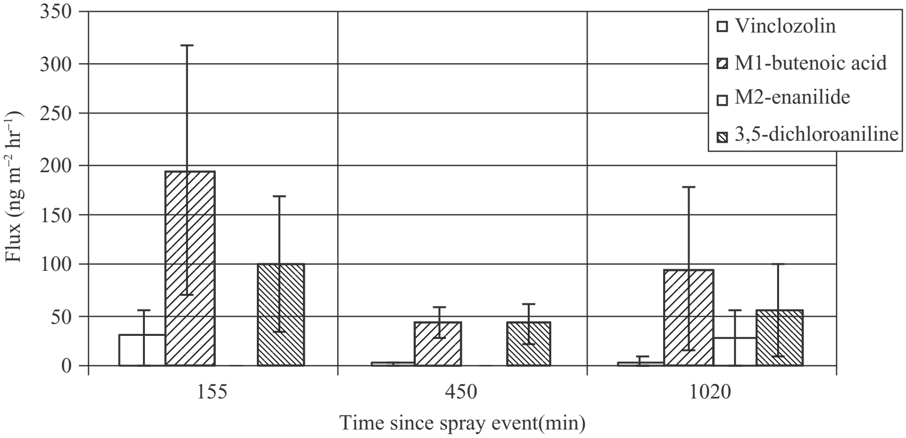

Figure 6.5 Flux of an agricultural fungicide after being sprayed onto soil. These results are from a laboratory chamber study of vinclozolin (5 mL of 2000 mg L^{-1} suspended in water); bars show the time-integrated atmospheric flux of organic compounds from nonsterile North Carolina Piedmont soil (aquic hapludult) with pore water pH of 7.5 following a 2.8-mm rain event and soil incorporation. Error bars indicate 95% confidence intervals. Vinclozolin [3-(3,5-dichlorophenyl)-5-methyl-5-vinyl-oxzoli-dine-2,4-dione], M1 (2-[3,5-dichlorophenyl)-carbamoyl]oxy-2-methyl-3-butenoic acid), and M2 (3′,5′-dichloro-2-hydroxy-2-methylbutyl-3-enanilide) are all suspected endocrine-disrupting compounds (i.e., they have been shown to affect hormone systems in mammals). This indicates that workers are not only potentially exposed to the parent compound (i.e., the pesticide that is actually applied) but to degradation products as the product is broken down in the soil.

From: D. A. Vallero and J. J. Peirce, "Transport and transformation of vinclozolin from soil to air," *Journal of Environmental Engineering*, 128(3), 261–268, 2002.

communities. Occupational exposures may also be disproportionately skewed in minority populations. For example, Hispanic workers can be exposed to higher concentrations of toxic chemicals where they live and work, in large part due to the nature of their work (e.g., agricultural chemical exposures can be very high when and shortly after fields are sprayed, as shown in Figure 6.5).

Biography: Ben Chavis

Ben Chavis was born in 1949 in Oxford, North Carolina, and served as a youth coordinator with the Southern Christian Leadership Conference, working in the 1960s with Reverand Martin Luther King, Jr. to desegregate southern schools. When he became an ordained minister, he continued to agitate for racial justice, and got into trouble in Wilmington, North Carolina, where he was convicted of conspiracy and arson. He spent nearly a decade in prison before the charges were thrown out in 1980.

On regaining his freedom, he became the director of the United Church of Christ's Commission for Racial Justice. In 1982 he came to the conclusion that the selection of the polychlorinated biphenyl (PCB) landfill for Warren County, North Carolina (very near his birthplace) had to be racially motivated. In his view, this poor, predominantly African-American county was singled out because its people were unlikely to protest the selection of the disposal site. He called this *environmental racism*, a term he later changed to *environmental justice*.

Teaming with Charles Lee of the EPA, he wrote the 1987 landmark report, "Toxic Wastes and Race in the United States," which documented the uneven distribution of environmentally undesirable land use in African-American and other minority communities. They found, for example, that in communities with two or more hazardous waste disposal facilities, the average minority population was more than three times that of communities without such facilities. The report also found that the U.S. EPA took longer to clean up waste sites in poorer areas than it took in more affluent neighborhoods.

In 1992, the U.S. Environmental Protection Agency (EPA) created the Office of Environmental Justice to coordinate the agency's EJ efforts, and in 1994, President Clinton signed Executive Order 12898, "Federal Actions to Address Environmental Justice in Minority and Low–Income Populations." This order directs that federal agencies attend to the environment and human health conditions of minority and low–income communities and requires that the agencies incorporate EJ into their missions. In particular, EJ principles must be part of the federal agency's day–to–day operation by identifying and addressing "disproportionately high and adverse human health and environmental effects of programs, policies and activities on minority populations and low–income populations."[35]

Biography: Charles Lee

Charles Lee (see Fig. B6.1) was Director of Environmental Justice for the United Church of Christ's Commission for Racial Justice and worked with Ben Chavis to author the 1987 report "Toxic Wastes and Race in the United States." Presently, Lee is with the U. S. Environmental Protection Agency working on the implementation of the executive order promoting environmental justice. He is also a lecturer at the Hunter College School of Health Sciences.

Figure B6.1 Charles Lee.

Case Study: Shintech Hazardous Waste Facility in St. James Parish, Louisiana

Before the moratorium on processing complaints went into effect, the EPA accepted a complaint from the Tulane Environmental Law Clinic in cooperation with other environmental groups with regard to a large toxic waste disposal facility that was to be constructed by Shintech, a Japanese firm, in the St. James Parish in Louisiana as the site for the facility. This parish is poor, predominantly African-American, and already the location of a vast array of industrial plants. As an enticement to the community, the company promised jobs in both the construction and operation of the plant. The complaint, however, stated that the emissions from this facility would create a disparate environmental impact on the minority population.

The allegations of disparate impact were supported in part by the fact that 18 toxic waste facilities were located in St. James Parish, and almost a quarter of all the pollutants produced in the state were emitted within a 4-mile radius of the parish. The case was accepted by the Office of Civil Rights (OCR) for review, but they decided not to report their conclusions until the EPA guidelines were published. During this administrative delay, Shintech decided to move the plant to a middle-class neighborhood, thus making the case moot. It should be noted that the new location was advantageous to Shintech since it was close to a Dow Chemical plant, and this allowed the waste to be pumped to the waste treatment facility, saving considerably on the cost of transport. Such decisions point to the complicated nature of environmental justice. Companies plan by optimizing a number of variables. In this case, the cost of pumping may have outweighed any savings from siting the plant in a lower-income neighborhood.

Case Study: Select Steel Corporation Recycling Plant in Flint, Michigan

In 1998, the Michigan Department of Environmental Quality approved an air emissions permit for a steel recycling minimill in Flint, Michigan, to be constructed by the Select Steel Corporation. A local group filed a Title VI complaint asserting discriminatory impact on a minority community. OCR accepted that case for review and was pressured into quick action by Select Steel's threat to move its plant to Ohio. EPA's delay in insisting on a careful review of this complaint caused significant political pressure. Michigan's Governor Engler criticized the EPA in a press conference, saying in part: "This is about every company that has ever had to deal with the EPA's reckless, ill-defined policy on environmental justice. . . .The EPA is imposing their bureaucratic will over this community and punishing the company with the latest environmental standards, all because of a baseless complaint. . . .The net result is that the EPA is a job killer."*

The *Detroit Free Press* relentlessly attacked the EPA, calling it a "rogue agency" and devoting large amounts of space to the controversy. Ultimately, the EPA decided in favor of the steel company, arguing that all of the permits had been granted correctly and that there were no emission regulations that would be violated from the emission of dioxin from the facility. In other words, if there is no standard, the effect of the emissions is not a problem from a regulatory standpoint.

Arguably, this decision is not whether all the emission guidelines have been met, but rather, whether the people affected by this facility are being treated fairly.

Ultimately, Select Steel decided to relocate its plant in Lansing, Michigan, instead of Flint, saying that they were tired of fighting local groups. Perhaps the most important "green" lesson from this case is that regulations are merely one of the drivers in a sound and sustainable design. Pollution limits are but one of the design specifications. A green design must go beyond regulatory mandates and must always lead to the best outcome for now and in the future.

*http://www.great-lakes.net/lists/enviro-mich/1998-09/msg00016.html, accessed June 29, 2005.

The Role of the Design Professions

Environmental injustice may seem intractable, but progress is being made. It is a problem that we are not going to solve in this book, although we do hope to give a few pointers on how to recognize and deal with injustice in a manner consistent with green design. The facts are that environmental inequality exists, and that often it is the minority populations in our country that bear the brunt of the pollution. We may help to solve some of these problems if the design community is increasingly aware of its influence on preventing injustice. As such, we point out a few things along the way that the individual professional can do to avoid inadvertently becoming a party to injustice and to take positive steps in one's profession to be empathic to all clients, not just those who procure our services directly.

The challenges posed by environmental justice are a blend of legal, moral, and technical factors with one common outcome (i.e., injustice). But designers are trained in technical matters. Yes, we practice in a milieu of law, politics, and social sciences, but our forte is within the realm of applying scientific principles.

The modern design challenge demands that we be better equipped technically and technologically as well as knowledgable in the social and human sciences. This calls for a systematic approach to education and practice, which is consistent with elements defined by the National Academy of Engineering for inclusion in their guiding strategies for the engineer of the future:

- Engaging engineers and other professionals in team-based problem solving
- Using technical tools
- Interacting with clients and managers to achieve goals
- Setting boundary conditions from economic, political, ethical, and social constraints to define the range of engineering solutions and to establish interactions with the public[36]
- Applying engineering processes to define and to solve problems using scientific, technical, and professional knowledge bases

Case Study: The Warren County PCB Landfill Revisited

As noted above, the Warren County PCB landfill was constructed in 1982 to contain soil that was contaminated by the illegal spraying of oil containing PCBs from over 340 km of highway shoulders. The landfill received soil contaminated with over 100,000 liters of oil from 14 North Carolina counties.

The landfill was located on a 142-acre tract about 3 miles south of the town of Warrenton, and held about 60,000 tons of contaminated soil collected solely from the contaminated roadsides. The U.S. EPA permitted the landfill under the Toxic Substances Control Act, which is the controlling federal regulation for PCBs. The state owns approximately 19 acres of the tract and Warren County owns the remaining acreage surrounding the state's property. The containment area of the landfill cell occupied approximately 3.8 acres that was enclosed by a fence. The landfill surface dimension was approximately 100 m × 100 m, with a depth of approximately 8 m of contaminated soil at the center. The landfill was equipped with both poly(vinyl chloride) and clay caps and liners, with a dual leachate collection system. The landfill was never operated as a commercial facility.

In 1994, a state-appointed Working Group, consisting of members of the community and representatives from the state, began an in-depth assessment of the landfill and a study of the feasibility of detoxification. Tests were conducted using landfill soil and several treatment technologies. In 1998, the working group selected base-catalyzed decomposition (BCD) as the most appropriate technology (see Fig. B6.2). Approximately $1.6 million in state funds had been spent by this time. In 1999, the Working Group fulfilled its mission and was re-formed into a community advisory board. In the BCD process, PCBs are separated from the soil using thermal desorption. Once separated, the PCBs are collected as a liquid for treatment by the BCD process. BCD is a nonincineration, chemical dechlorination process that transforms PCBs, dioxins, and furans into nontoxic compounds. In the process, chlorine atoms are chemically removed from the PCB and dioxin–furan molecules and replaced with hydrogen atoms. This converts the compounds to biphenyls, which are nonhazardous. Treated soil is returned to the landfill and the organics from the BCD process are recycled as a fuel or disposed off-site as nonhazardous waste.

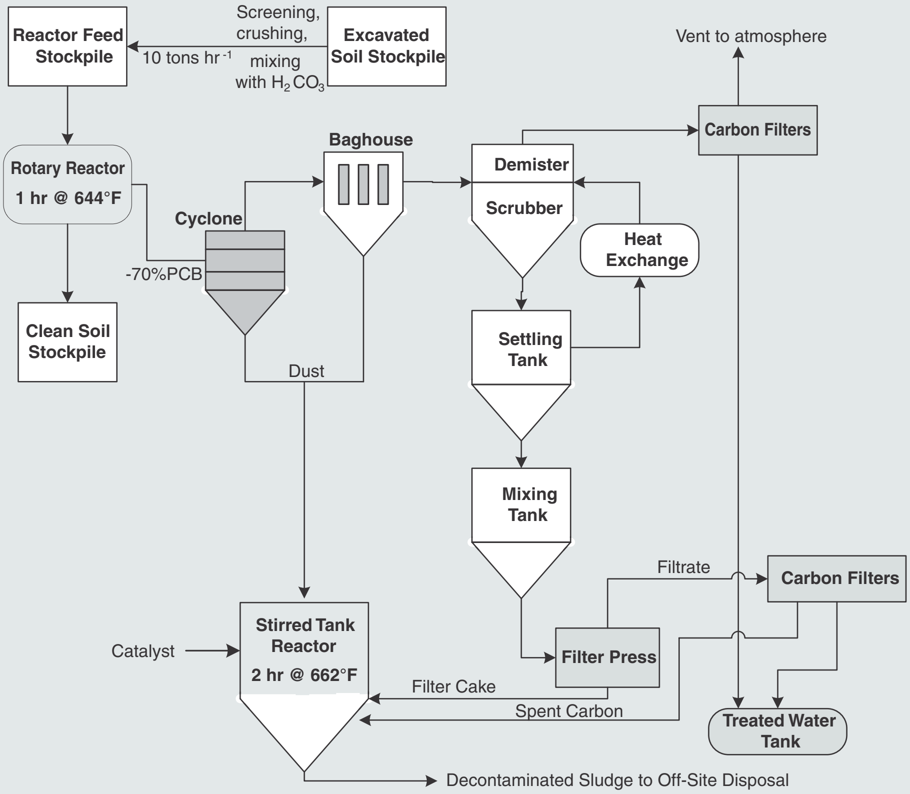

Figure B6.2 Base catalyzed decomposition. This is the process recommended to treat PCB-contaminated soil stored in Warren County, North Carolina.

From: Federal Remediation Technologies Roundtable, *Screening Matrix and Reference Guide*, 4th ed., FRTR, Washington, DC, 2002.

The cleanup target of 200 parts per billion (ppb) was established by the working group for the landfill site and was made a statutory requirement by the North Carolina General Assembly. The EPA cleanup level for high-occupancy usage is 1 part per million (ppm). EPA's examples of high-occupancy areas include residences, schools, and day care centers. The plan is an example of a targeted and precautionary design, since these areas are likely to have greater exposures than those at a landfill, which limits contact and access, and because the cleanup target is five times lower than the EPA requirement.* The removal of PCBs from the soil will eliminate further regulation of the site and permit flexible uses of the site after clean up.

A public bid opening was held on December 22, 2000 for the site detoxification contract. The IT Group, with a bid of $13.5 million, was the low bidder. Existing funds were sufficient to fund phase I. A contract was entered into with the IT Group, and a notice to proceed was issued on March 12, 2001. Site preparation work was completed in December 2001. Work included the construction of concrete pads and a steel shelter for the processing area, the extension of county water, an upgrade of electrical utilities, and the establishment of sediment and erosion control measures.

The treatment equipment was delivered in May 2002. An open house was held on site the next month so that community members could view the site and equipment before startup. Initial tests with contaminated soil started at the end of August 2002. The EPA demonstration test was performed in January 2003. An interim operations permit was granted in March 2003 based on the demonstration test results. Soil treatment was completed in October 2003. A total of 81,600 tons of material was treated from the landfill site. The treated materials included the original contaminated roadside soil and soil adjacent to the roadside material in the landfill that had been cross-contaminated. The original plan specified using the BCD process to destroy the PCBs after thermal desorption separated them from the soil. With only limited data available to estimate the quantity of liquid PCBs that would be collected, conservative estimates were used to design the BCD reactor. In practice, the quantity of PCBs recovered as liquid was much less than anticipated. Thus, the BCD reactor tanks were too large to be used for the three-run demonstration test required under TSCA to approve the BCD process. As an alternative, one tankload of liquid containing PCBs was shipped to an EPA-permitted facility for destruction by incineration. Most of the equipment was decontaminated and demobilized from the site by the end of 2003. Site restoration was completed in the spring when vegetation became established. The total cost of the project was $17.1 million.

*Similar protective approaches have been used frequently in emergency response and remedial efforts, such as those that followed the attacks on the World Trade Center towers. For example, the risk assessments assumed long-term exposures (e.g., 30 years) to contaminants released by the fire and fugitive dust emissions, even though the exposures were significantly shorter.

PROFESSIONAL COMPETENCE

Design professionals apply the physical sciences. Since designers are technical professionals, they depend on scientific breakthroughs. Science and technologies are drastically and irrevocably changing. The designer must stay abreast of new developments. The scale is simultaneously increasing and decreasing. We think about the planet, but the nano scale, where the design scales structures and systems are a few angstroms, is receiving increasing attention.

Green Design: Both Integrated and Specialized

Professional specialization has both advantages and disadvantages. The principal advantage is that the practicing designer can focus more sharply than can a generalist on a specific discipline. The principal disadvantage is that integrating the various parts can be challenging. For example, in a very complex design, only a few people can see the overall goals. Thus, those working in specific areas may not readily identify duplication or gaps that they assume are being addressed by others.

The work of technical professions is both the effect and the cause of modern life. When undergoing medical treatment and procedures, people expect physicians, nurses, emergency personnel, and other health care providers to be current and capable. Likewise, society's infrastructures, building, roads, electronic communications, and other modern necessities and conveniences are expected to perform as designed by competent engineers designers and planners. But how does society ensure that these expectations are met? Much of the answer to this question is that society cedes a substantial amount of trust to a relatively small group of experts, the professionals in increasingly complex and complicated disciplines that have grown out of the technological advances that began in the middle of the twentieth century and grew exponentially in its waning decades.

Within this highly complex, contemporary environment, practitioners must ensure that they are doing what is best for the profession and what is best for the public and client. This *best practice* varies by profession and even within a single professional discipline, so the actual codified *rules* (codes of ethics, either explicit or implicit) must be tailored to the needs of each group. However, many of the ethical standards are quite similar for most design professions. For example, people want to know that the professional is trustworthy. The trustworthiness is a function of how good the professional is in the chosen field and how ethical the person is in practice. Thus, the professional possesses two basic attributes, subject matter knowledge and character. Maximizing these two attributes enhances professionalism.

Thus, we can apply Kant's categorical imperative to green design as the sustainability imperative: "Design and build only in ways which you can at the same time will that it should be the future in which you would want to live."[37]

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well be legal, and even professionally permissible, but may still fall below the ethical threshold if reasonable people consider it to be wrong.

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18. Hence, the engineering profession's emphasis on experience and mentorship.
19. J. A. Rawls, *A Theory of Justice,* Harvard University Press, Cambridge, MA, 1785, and Kant, *Foundations*, 1785.
20. This wording is quite interesting. It omits *public safety*. However, safety is added under professional obligations that biomedical engineers "use their knowledge, skills, and abilities to enhance the safety, health, and welfare of the public." The other interesting word choice is *consideration*. Some of us would prefer *obligations* instead. These compromises may indicate the realities of straddling the design and medical professions. For example, there may be times when the individual patient needs supersede those of the general public, and vice versa.
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22. Martin Luther King, "Letter from Birmingham Jail," in *Why We Can't Wait*, HarperCollins, New York, 1963.
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24. For example, this is the fourth canon of the American Society of Civil Engineers' *Code of Ethics*, adopted in 1914 and most recently amended November 10, 1996. This canon reads: "Engineers shall act in professional matters for each employer or client as faithful agents or trustees, and shall avoid conflicts of interest."
25. Even this is a challenge for environmental justice communities, since certain sectors of society are less likely to visit hospitals or otherwise receive early health care attention. This is not only a problem of assessment, but can lead to more serious, long-term problems compared to those of the general population.
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28. This harkens back to the Constitution's requirement of equal protection.
29. Pronounced "Fonzy" like that of the nickname for the character Arthur Fonzerelli, portrayed by Henry Winkler in the television show, *Happy Days*.
30. This is understandable if the agency is in the business of something not directly related to environmental work, but even the natural resources and environmental agencies have asserted that there is no significant impact to their projects. It causes the cynic to ask, then, why they are engaged in any project that has no significant impact. The answer is that the term *significant impact* is really understood to mean "significant adverse impact" to the human environment.
31. I attribute this quote to Timothy Kubiak, one of Professor Caldwell's former graduate students in Indiana University's Environmental Policy Program. Kubiak has since gone on to become a successful environmental policymaker in his own right, first at EPA and then at the Fish and Wildlife Service.
32. B. B. Marriott, "Land use and development," Chapter 5 in *Environmental Impact Assessment: A Practical Guide*, McGraw-Hill, New York, 1997.
33. See: M. Ritzdorf, 1997, "Locked out of paradise: contemporary exclusionary zoning, the Supreme Court, and African Americans, 1970 to the present," in *Urban Planning and the African American Community: In the Shadows*, J. M. Thomas and M. Ritzdorf, Eds., Sage Publications, Thousand Oaks, CA, 1997.
34. Commission for Racial Justice, United Church of Christ, *Toxic Wastes and Race in the United States*, UCC, 1987.
35. Presidential Executive Order 12898.
36. National Academy of Engineering, *Educating the Engineer of 2020: Adapting Engineering Education to the New Century*, National Academies Press, Washington, DC, 2005.
37. Kant, *Foundations*.

chapter 7

The Carbon Quandary: Essential and Detrimental

In recent years, carbon has become a highly publicized element, mainly because of its suspected role in global warming. But carbon is intrinsically worthy of study. For starters, carbon has four electrons in its outermost shell, so it is likely to share four to fill its outermost shell. This means that it readily forms covalent bonds and is the main reason that so many organic compounds are possible. Carbon also forms polymers (linked chemical units) readily at ambient temperatures and pressures found on Earth, requiring no super heating. These include cellulose, lignins, and other polymers that are abundant in plant and animal tissues. Carbon is also the basis of synthetic polymers, which are common in almost every aspect of contemporary life and provide the potential for sustainable solution to many of the greatest challenges as new materials are formed from composites (needed in health care, industry, clothing, etc.)

Living systems both reduce and oxidize carbon. *Reduction* is the act of gaining electrons, *whereas* oxidation is the act of losing electrons from the outermost shell. Reduction often takes place in the absence of molecular oxygen (O_2), such as in the rumen of cattle, in sludge at the bottom of a lagoon, or in buried detritus on the forest floor. Anaerobic bacteria get their energy by reduction, breaking down organic compounds into methane (CH_4) and water.

Conversely, aerobic microbes get their energy from oxidation, forming carbon dioxide (CO_2) and water. Plants absorb CO_2 for photosynthesis, the process by which plants convert solar energy into biomass and release O_2 as a by-product. Thus, the essential oxygen is actually the waste product of photosynthesis and is derived from carbon-based compounds. Respiration generates carbon dioxide as a waste product of oxidation that takes place in organisms, so there is a balance between green plants' uptake of CO_2 and release of O_2 in photosynthesis and the uptake of O_2 and release of CO_2 in respiration by animals, microbes, and other organisms.

Combined with hydrogen, carbon forms hydrocarbons—which can be both good and bad, depending on their mobility toxicity and other individual characteristics. For example, those released when burning fossil fuels can be toxic and lead to smog, but hydrocarbons are essential as food. They make nature colorful, such as the carotenoids (organic pigment in photosynthetic organisms, including algae), and evoke our sense of smell, such as the terpenes produced by a variety of pines and other coniferous trees. They are also the primary constituents of essential oils in plants and flowers used as natural flavor additives in food. Hydrocarbons also make up medicines and myriad other products that are part of our daily lives.

Combined with oxygen and hydrogen, carbon forms many biological compounds, including sugars, cellulose, lignin, chitins, alcohols, fats, and esters. Combined with nitrogen, carbon forms *alkaloids*, naturally occurring amines produced by plants and animals, which combine to form proteins. Combined with sulfur, carbon is the source of antibiotics, proteins, and amino acids. Combined with phosphorus and these other elements, carbon forms ribonucleic acid (RNA) and deoxyribonucleic acid (DNA), creating the building blocks and chemical codes of life. Even new technologies are rooted in carbon. For example, nanomaterials are often carbon-based, such as carbon 60 (^{60}C). Interestingly, these spherical structures, consisting of 60 carbon atoms, are called *fullerenes* or *Buckyballs*, after the famous designer Buckminster Fuller, in honor of his innovative geodesic domes and sphreres. When fullerenes combine, they are linked into *nanotubes*.

Sidebar: Applying the Synthovation/Regenerative Model: Nanotechnology

Nanotechnology is an example of an emerging technology that can be good or bad. Research at the very small scale (< 100 nm) is already producing promising results in medicine, coatings, and sensors. In fact, nanomaterials are being used to clean up hazardous waste sites. However, like biotechnology before them, these technologies are met with skepticism by the lay public and scientists alike. One of the best ways to balance utility with risk is to take an integrated and systematic view. In particular, the engineering community is calling on the perspectives of all of the design disciplines, along with those of ethicists, policymakers, and the public at the early stages of nanotechnological advancement. We must be intellectually honest about the value, practicality, and hazards of emerging technologies. It is short-sighted to advocate a ban on them, but just as ridiculous to accept them as "good" merely on blind faith. Duke University is currently endeavoring to find ways to teach researchers to be sensitive to possible misuse and dangers of nanotechnologies, emphasizing the movement and fate of nanoparticles in the environment, possible hazards and risks to users of nanomaterials in products, and health and safety issues in the lab.*

* D. A. Vallero, "Beyond responsible conduct in research: new pedagogies to address macroethics of nanobiotechnologies," *Journal of Long-Term Effects of Medical Implants*, 2007 (in press).

In teaching green engineering and sustainable design, especially to first-year engineering students, open-ended questions can be quite revealing. Here is one: "Is carbon good or bad?" Most students who take our courses have learned that the best answer is almost always, "It depends." This leads to a follow-up question: "Okay, on *what* does it depend?" This usually leads to tortuous discussion of what (e.g., the chemical species), when (e.g., at the beginning of photosynthesis or at the end of respiration), where (e.g., in the soil versus the atmosphere), and how (e.g., the processes by which carbon cycles through the environment). This also gives the instructor an opportunity to discuss *why* carbon is important for good or ill.

Carbon is at the center of every environmental discussion. Most recently, this is in large part because the two most prominent greenhouse gases, carbon dioxide and methane, are carbon-based compounds. However, these are just two of the carbon compounds that are cycled continuously through the environment (see Fig. 7.1).

Figure 7.1 demonstrates the importance of carbon sinks and sources. For example, if carbon can remain sequestered in the soil, roots, sediment, and other compartments, it is not released to the atmosphere. Thus, it cannot have an impact on the greenhouse effect. Even relatively small amounts of methane and carbon dioxide can profoundly increase the atmosphere's greenhouse potential.

Suffice it to say that carbon is an amazing element. It can bond to itself and to other elements in a myriad of ways. In fact, it can form single, double, and triple bonds with itself. This makes possible millions of organic compounds. An *organic compound* is a compound that includes at least one carbon-to-carbon or carbon-to-hydrogen bond.

By far most pesticides and toxic substances include carbon. However, all living tissues so consist of organic compounds. All life on Earth is carbon-based. Biochemistry is known as the chemistry of life, or at least the chemistry of what takes place in living systems. Biochemistry is a subdiscipline of organic chemistry.

Slight changes to an organic molecule can profoundly affect its behavior in the environment. For example, there are large ranges of solubility for organic compounds, depending on the presence of polar groups in their structure. The addition of an alcohol group to *n*-butane to produce 1-butanol, for example, increases the solubility several orders of magnitude. This means that an engineer deciding to use an alcohol-based compound in a manufacturing step is making

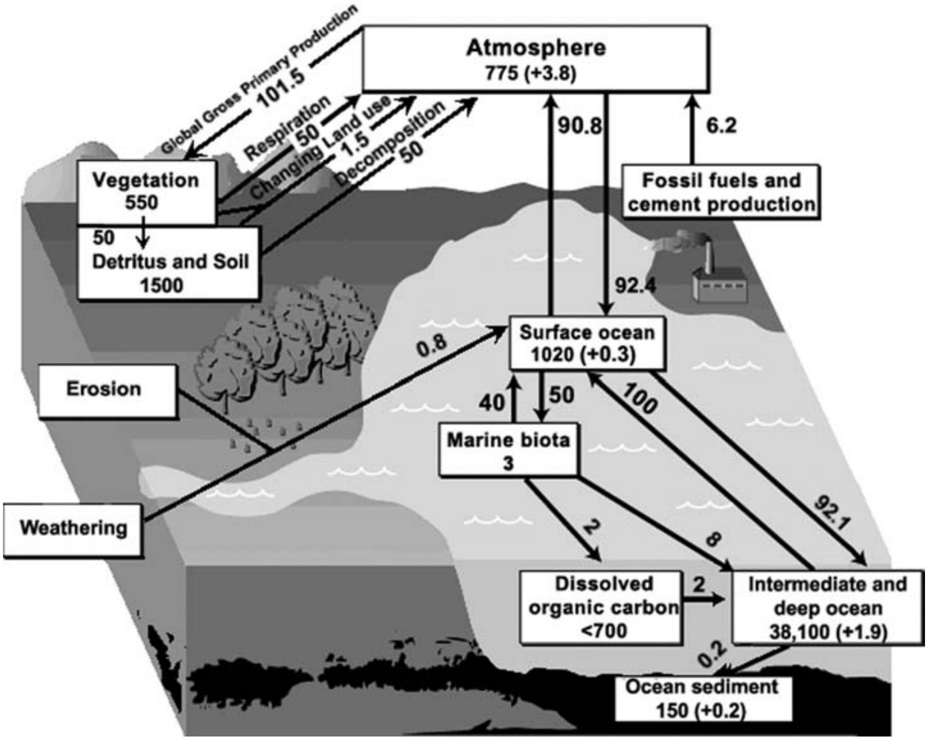


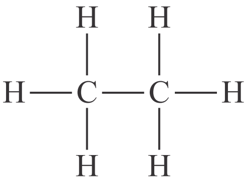
Figure 7.1 Global carbon cycle, 1992 to 1997. Boxes represent the carbon pool, expressed in gigatons (Gt) of carbon. (*Note:* 1Gt C $= 10^{15}$ g C.) Annual increments are expressed in Gt C per year (shown in parentheses). All fluxes indicated by the arrows are expressed in Gt C per year. The inferred net terrestrial uptake of 0.7 Gt C per year considers gross primary production ($\sim$101.5), plant respiration ($\sim$50), decomposition ($\sim$50), and additional removal from the atmosphere directly or indirectly, through vegetation and soil and eventual flow to the ocean through the terrestrial processes of weathering, erosion, and runoff ($\sim$0.8). Net ocean uptake ($\sim$1.6) considers air–sea exchange ($\sim$92.4 gross uptake, $-$90.8 gross release). As the rate of fossil-fuel burning increases and CO_2 is released to the atmosphere, it is expected that the fraction of this C remaining in the atmosphere will increase, resulting in a doubling or tripling of the atmospheric amount in the coming century.

From M. Post, Oak Ridge National Laboratory, http://cdiac.ornl.gov/pns/graphics/c_cycle.htm, accessed July 25, 2007.

a decision, knowingly or otherwise, that this compound is more likely to end up in the water than if the original nonhydrolyzed form were used. This does not mean that the choice is a bad one. It could be good; since the process also lowers the vapor pressure, the alcohol may be easier to keep from being released from stacks and vents. The key is knowing ahead of time that the choice has consequences, and to plan for them accordingly.

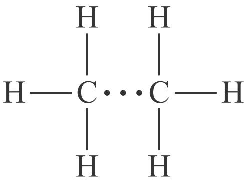
Organic compounds can be further classified into two basic groups: aliphatics and aromatics. Hydrocarbons are the most fundamental type of organic compound. They contain only the elements carbon and hydrogen. We hear a lot about these compounds in air pollution discussions. As mentioned, the presence of hydrocarbons is an important part of the formation of smog. For example, places such as Los Angeles that have photochemical oxidant smog problems are looking for ways to reduce the amount of hydrocarbons released to the air.

Aliphatic compounds are classified into a few chemical families. Each carbon normally forms four covalent bonds. Alkanes are hydrocarbons that form chains, with each link comprised of the carbon. A single link is CH_4, methane. The carbon chain length increases with the addition of carbon atoms. For example, ethane’s structure is



$$\begin{array}{ccccccc} & & H & & H & & \\ & & | & & | & & \\ H & - & C & - & C & - & H \\ & & | & & | & & \\ & & H & & H & & \end{array}$$

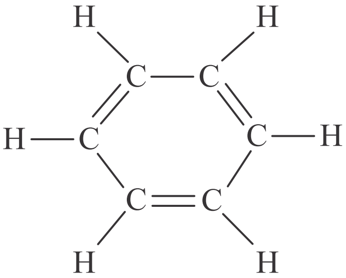
and the protypical alkane structure is



$$\begin{array}{ccccccc} & & H & & H & & \\ & & | & & | & & \\ H & - & C & \cdots & C & - & H \\ & & | & & | & & \\ & & H & & H & & \end{array}$$

The alkanes contain a single bond between carbon atoms and include the simplest organic compound, methane (CH_4), and its derivative “chains,” such as ethane (C_2H_6) and butane (C_4H_{10}). Alkenes contain at least one double bond between carbon atoms. For example, 1,3-butadiene’s structure is $CH_2{=}CH{-}CH{=}CH_2$. The numbers “1” and “3” indicate the position of the double bonds. The alkynes contain triple bonds between carbon atoms, the simplest being ethyne, $CH{\equiv}CH$, commonly known as acetylene (the gas used by welders).

The *aromatics* are all based on the six-carbon configuration of benzene (C_6H_6):



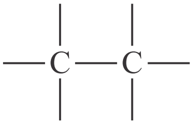
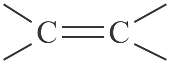
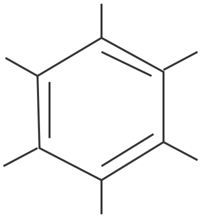
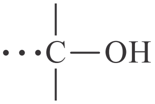
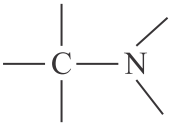
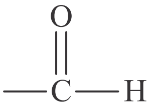
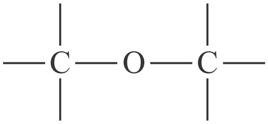
The carbon–carbon bond in this configuration shares more than one electron, so that benzene’s structure allows for resonance among the double and single bonds (i.e., the actual benzene bonds flip locations). Benzene is the average of two equally contributing resonance structures.

The term *aromatic* comes from the observation that many compounds derived from benzene are highly fragrant, such as vanilla, wintergreen oil, and sassafras. Aromatic compounds thus contain one or more benzene rings. The rings are *planar*; that is, they remain in the same geometric plane as a single unit. However, in compounds with more than one ring, such as the highly toxic polychlorinated biphenyls (PCBs), each ring is planar, but the structure of the rings bound together may or may not be planar. This is actually a very important property for toxic compounds. It has been shown that some planar aromatic compounds are more toxic than their nonplanar counterparts, possibly because living cells may be more likely to allow planar compounds to bind to them and to produce nucleopeptides that lead to biochemical reactions associated with cellular dysfunctions such as cancer or endocrine disruption.

Aliphatic and aromatic compounds can both undergo substitutions of the hydrogen atoms. These engender new properties to the compounds, including changes in solubility, vapor pressure, and toxicity. For example, halogenation (substitution of a hydrogen atom with a halogen) often makes an organic compound much more toxic: Trichoroethane is a highly carcinogenic liquid that has been found in drinking water supplies, whereas nonsubstituted ethane is a gas with relatively low long-term toxicity. This is also why one of the means of treating wastes contaminated with chlorinated hydrocarbons and aromatic compounds involves dehalogenation techniques. The important functional groups that are part of many organic compounds are shown in Table 7.1. Green design success or failure can hinge on the type of organic compounds resulting from reactions. A step that leads to a chlorinated compound, for example, can be made greener if that step is removed or if it generates a less toxic, nonhalogenated compound instead. Thus, the designer needs at least a rudimentary understanding of these structures.

Different structures of organic compounds can induce very different physical and chemical characteristics, as well as change the bioaccumulation and toxicity of these compounds. For example, the differences between an estradiol and a testosterone molecule may seem small, but they cause significant differences in the growth and reproduction of animals. The very subtle differences between an estrogen and an androgen, female and male hormones, respectively, can be seen in these structures. Incremental changes to a simple compound such as ethane can make for large differences (see Table 7.2). Replacing two or three hydrogens with chlorine atoms makes for differences in toxicities between the nonhalogenated and the chlorinated forms. The same is true for the simplest aromatic, benzene. Substituting a methyl group for one of the hydrogen atoms forms toluene. Replacing a hydrogen with a hydroxyl group is equally significant. For example, dry cleaning operations have progressively switched solvents, from very toxic, chlorinated compounds to safer ones. In fact, many dry cleaners' now use chlorinefree processes, especially those that take advantage of CO_2 when it becomes supercritical. At sufficiently high pressure, CO_2 can dissolve most

Table 7.1 Structures of Organic Compounds

Chemical Class	Functional Group
Alkanes	
Alkenes	
Alkynes	$-C\equiv C-$
Aromatics	
Alcohols	
Amines	
Aldehydes	
Ether	

(*continued*)

Table 7.1 (*Continued*)

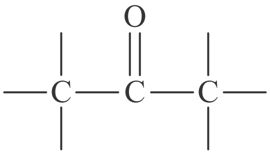
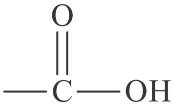
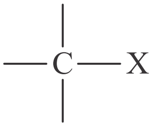
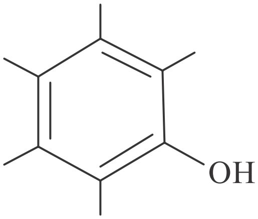
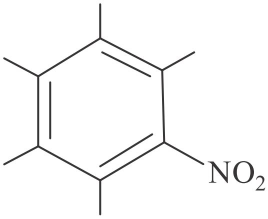
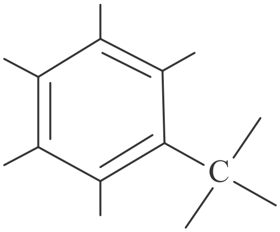
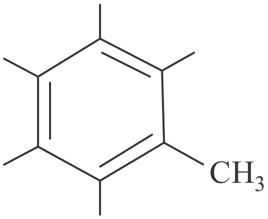
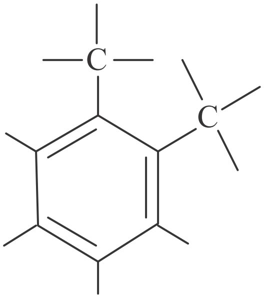
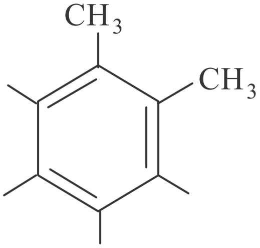
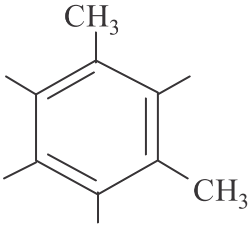
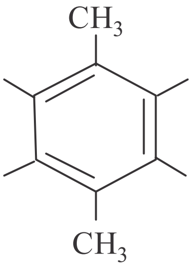
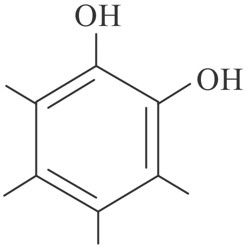
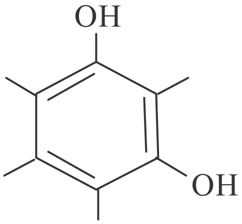
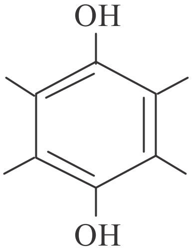
Chemical Class	Functional Group
Ketones	 $-\overset{\mid}{\underset{\mid}{C}}-\overset{O}{\overset{\|}{C}}-\overset{\mid}{\underset{\mid}{C}}-$
Carboxylic acids	 $-\overset{O}{\overset{\|}{C}}-OH$
Alkyl halides[a]	 $-\overset{\mid}{\underset{\mid}{C}}-X$
Phenols (aromatic alcohols)	
Substituted aromatics (substituted benzene derivatives):	
Nitrobenzene	
Monosubstituted alkylbenzenes	

Table 7.1 (*Continued*)

Chemical Class	Functional Group
Toluene (simplest monosubstituted alky benzene)	
Polysubstituted alkylbenzenes	
1,2-Alkyl benzene (also known as *ortho* or *o*-. . .)	
1,2-Xylene or *ortho*-xylene (*o*-xylene)	
1,3-Xylene or *meta*-xylene (*m*-xylene)	

(*continued*)

Table 7.1 (*Continued*)

Chemical Class	Functional Group
1,4-Xylene or *para*-xylene (*p*-xylene)	
Hydroxyphenols (do not follow general nomenclature rules for substituted benzenes)	
Catechol (1,2-hydroxiphenol)	
Resorcinol (1,3-hydroxiphenol)	
Hydroquinone (1,4-hydroxiphenol)	

[a] The letter "X" commonly denotes a halogen (e.g., fluorine, chlorine, or bromine) in organic chemistry. However, since this book is an amalgam of many scientific and design disciplines, where *x* often means an unknown variable and horizontal distance on coordinate grids, this rule is sometimes violated. Simply note that when consulting manuals on the physicochemical properties of organic compounds, such as those for pesticides and synthetic chemistry, the "X" usually denotes a halogen.

Table 7.2 Incremental Differences in Molecular Structure Leading to Changes in Physicochemical Properties and Hazards

Compound	Physical State at 25°C	$-\log P^{\circ}$ Solubility in H_2O at 25°C (mol L^{-1})	$-\log$ Vapor Pressure at 25°C (atm)	Worker Exposure Limits (parts per million)	Regulating Agency
Methane, CH_4	Gas	2.8	−2.4	25	Canadian Safety Association
Tetrachloromethane (carbon tetrachloride), CCl_4	Liquid	2.2	0.8	2 short-term exposure limit (STEL) = 60 min	National Institute of Occupation Health Sciences (NIOSH)
Ethane, C_2H_6	Gas	2.7	−1.6	None (simple asphyxiant)	Occupational Safety and Health Administration (OSHA)
Trichloroethane, $C_2H\,Cl_3$	Liquid	2.0	1.0	450 (STEL-15 min)	OSHA
Benzene, C_6H_6	Liquid	1.6	0.9	5	OSHA
Phenol, C_6H_6O	Liquid	0.2	3.6	10	OSHA
Toluene, C_7H_8	Liquid	2.3	1.4	150	UK Occupational and Environmental Safety Services

oil-based compounds readily (and these are the ones that typically need to be removed from clothing).

The lessons for green design are many. There are uncertainties in using surrogate compounds to represent entire groups of chemicals (since a slight change can change the molecule significantly). However, there have been substantial advances in green chemistry and computational chemistry as tools to prevent dangerous chemicals from reaching the marketplace and the environment before they are manufactured. Subtle differences in molecular structure can render molecules safer while maintaining the characteristics that make them useful in the first place, including their market value.

CARBON AND RAIN

By far most carbon-based compounds are organic, but a number of inorganic compounds are also important. In fact, the one that is getting the most attention for its role in climate, carbon dioxide, is an inorganic compound owing to its carbon atom lacking a covalent bond with other carbon or hydrogen atoms. Other important inorganic carbon compounds include the pesticides sodium cyanide (NaCN) and potassium cyanide (KCN) and the toxic gas carbon monoxide (CO). Inorganic compounds include inorganic acids such as carbonic acid (H_2CO_3)

and cyanic acid (HCNO) and compounds derived from reactions with the anions carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-).

Interestingly, warming is not the only climate phenomenon affected by the carbon cycle. Inorganic carbon compounds also play a key role in acid rain. In fact, normal, uncontaminated rain has a pH of about 5.6, owing largely to its dissolution of carbon dioxide, CO_2. As water droplets fall through the air, the CO_2 in the atmosphere becomes dissolved in the water, setting up an equilibrium condition:

$$CO_2 \text{ (gas in the air)} \leftrightarrow CO_2 \text{ (dissolved in the water)} \tag{7.1}$$

The CO_2 in the water reacts to produce hydrogen ions as

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^- \tag{7.2}$$

$$HCO_3^- \leftrightarrow 2H^+ + CO_3^{2-} \tag{7.3}$$

Given the mean partial pressure of CO_2 in the air is 3.0×10^{-4} atm, it is possible to calculate the pH of water in equilibrium. Partial pressure can be thought of as a concentration. That is, each of the gases in air exert a relative percentage of the total pressure of the air. Since nitrogen molecules are the largest percentage of all the air molecules, they exert the largest share of partial pressure in air. Likewise they are the highest concentration of the air mixture. Such chemistry is always temperature dependent, so let us assume that the air is 25°C. We can also assume that the mean concentration of CO_2 in the troposphere is 350 ppm (although 370 ppm may be a better estimate), but this concentration is rising by some estimates at a rate of 1.6 ppm per year. The concentration of the water droplet's CO_2 in water in equilibrium with air is obtained by inserting this partial pressure into the Henry's law equation,[1] which is a function of a substance's solubility in water and its vapor pressure:

$$p_{CO_2} = K_H[CO_2]_{aq} \tag{7.4}$$

The change from carbon dioxide in the atmosphere to carbonate ions in water droplets follows a sequence of equilibrium reactions:

$$CO_{2(g)} \xleftrightarrow{K_H} CO_{2(aq)} \xleftrightarrow{K_r} H_2CO_{3(aq)} \xleftrightarrow{K_{a_1}} HCO_{3(aq)^-} \xleftrightarrow{K_{a_2}} CO_{3(aq)}{}^{2-} \tag{7.5}$$

A more precise term for acid rain is *acid deposition*, which comes in two forms: wet and dry. *Wet deposition* refers to acidic rain, fog, and snow. The *dry deposition* fraction consists of acidic gases or particulates. The strength of the effects depends on many factors, especially the strength of the acids and the buffering capacity of soils. Note that this involves every species in the carbonate equilibrium reactions of equation (7.5) (see Fig. 7.2). The processes that release carbonates increase the

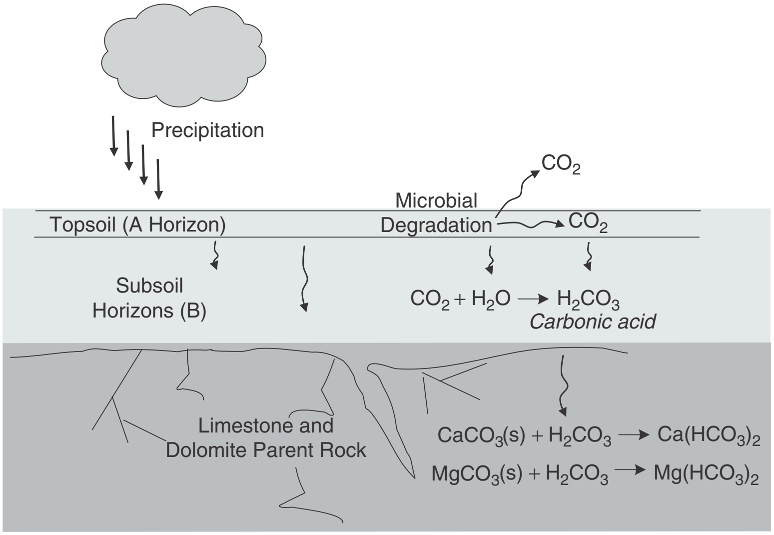


Figure 7.2 Biogeochemistry of carbon equilibrium. The processes that release carbonates are responsible for much of the buffering capacity of natural soils against the effects of acid rain.

buffering capacity of natural soils against the effects of acid rain. Thus, carbonate-rich soils such as those of central North America are able to withstand even elevated acid deposition compared to thin soil areas such as those in the Canadian Shield, the New York Finger Lakes region, and much of Scandinavia.

The concentration of carbon dioxide is constant, since the CO_2 in solution is in equilibrium with the air, which has a constant partial pressure of CO_2. The two reactions and ionization constants for carbonic acid are

$$H_2CO_3 + H_2O \leftrightarrow HCO_3^- + H_3O^+ \qquad K_{a1} = 4.3 \times 10^{-7} \qquad (7.6)$$

$$HCO_3^- + H_2O \leftrightarrow CO_3^{2-} + H_3O^+ \qquad K_{a2} = 4.7 \times 10^{-11} \qquad (7.7)$$

K_{a1} is four orders of magnitude greater than K_{a2}, so the second reaction can be ignored for environmental acid rain considerations. The solubility of gases in liquids can be described quantitatively by Henry's law, so for CO_2 in the atmosphere at 25°C, we can apply the Henry's law constant and the partial pressure to find the equilibrium. The K_H value for $CO_2 = 3.4 \times 10^{-2}$ mol L^{-1} atm^{-1}. We can find the partial pressure of CO_2 by calculating the fraction of CO_2 in the atmosphere. Since the mean concentration of CO_2 in Earth's troposphere is 350 ppm by volume in the atmosphere, the fraction of CO_2 must be 350 divided by 1 million, or 0.000350 atm.

Thus, the carbon dioxide and carbonic acid molar concentration can now be found:

$$[CO_2] = [H_2CO_3] = 1.2 \times 10^{-5}\, M = 3.4 \times 10^{-2}\,\mathrm{mol\,L^{-1}\,atm^{-1}} \times 0.000350\,\mathrm{atm}$$

The equilibrium is $[H_3O^+] = [HCO^-]$. Taking this and our carbon dioxide molar concentration yields

$$\begin{aligned} K_{a1} = 4.3 \times 10^{-7} &= \frac{[HCO_3{}^-][H_3O^+]}{CO_2} = \frac{[H_3O^+]^2}{1.2 \times 10^{-5}} \\ [H_3O^+]^2 &= 5.2 \times 10^{-12} \\ [H_3O^+] &= 2.3 \times 10^{-6}\,\text{M} \end{aligned}$$

Or, since pH is the negative logarithm of the molar concentration of hydronium ions, the pH of the droplet is 5.7.

If the concentration of CO_2 in the atmosphere increases to the very reasonable estimate of 400 ppm, what will happen to the pH of "natural rain"?

The new molar concentration would be 3.4×10^{-2} mol L^{-1} atm^{-1} $\times$ 0.000400 atm $= 1.4 \times 10^{-5}$ M, so

$$\begin{aligned} 4.3 \times 10^{-7} &= \frac{[H_3O^+]^2}{1.4 \times 10^{-5}} \\ [H_3O^+]^2 &= 5.8 \times 10^{-12} \\ [H_3O^+] &= 2.4 \times 10^{-6}\,\text{M} \end{aligned}$$

Thus, the droplet pH would decrease to about 5.6. That is, the new pH is $-\log[H_3O^+] = -\log[3.0 \times 10^{-6}] = 5.6$. This means that the incremental increase in atmospheric carbon dioxide can be expected to contribute to greater acidity in natural rainfall. This increase in acidity (decrease in pH) is actually less than 0.1 pH units due to rounding. However, considering this would take place throughout the lower portion of the entire Earth's atmosphere, it is quite significant. Also, keep in mind that pH is a log scale.

Most of the concern for acid rain has rightly been concerned with compounds other than CO_2, notably oxides of sulfur and nitrogen, that are released to the troposphere. These compounds can dramatically decrease the pH of rain. However, the increase in CO_2 means that the pH of rainfall, which is not neutral to begin with, can adversely affect fish and wildlife in and around surface waters with even lower concentrations of sulfur and nitrogen compounds. Thus, as CO_2 builds up in the atmosphere, there will be a concomitant increase in rainfall acidity if all other factors remain constant (e.g., concentrations of sulfur and nitrogen compounds do not continue to decline).

GLOBAL WARMING

The average temperature of Earth is difficult to measure, but most measurements show a very small overall change that would not be detectable to humans due to short-term and regional variations. Overall, however, a majority of scientific evidence appears to indicate that the temperature of Earth is increasing. There have been wide fluctuations in mean global temperatures, such as the ice ages, but on balance the mean temperature has remained constant, prompting some scientists to speculate some whimsical causes for such consistency. One person who has helped to lend scientific credibility to the debate is Charles Keeling, an atmospheric scientist who measured CO_2 concentrations in the atmosphere using an infrared gas analyzer. Since 1958, these data have provided the single most important piece of information on global warming and are now referred to as the Keeling curve in honor of the scientist. The curve shows that there has been more than a 15% increase in CO_2 concentration in the troposphere, which is a substantial rise given the short time that measurements have been taken. If we extrapolate backward, it is likely that our present CO_2 levels are double what they were in pre–industrial revolution times, providing ample evidence that global warming is indeed occurring.[2]

Sidebar: Applying the Synthovation/Regenerative Model: Land

Humans have been engaged in land development for thousands of years, but the twentieth century saw an acceleration of an alteration to natural landforms. This rapid change has been accompanied by a weakening of the sense of stewardship toward the environment held by the earliest settlers. The patterns of early settlement suggest an intimate understanding of a building site in a way that most modern, technologically sophisticated buildings seem to ignore. Studies by the late professor Gordon Willey of Harvard University suggest that people living in prehistoric Mayan settlements in the Belize valley had an understanding of the carrying capacity of the land and settlement density.

Evidence suggests that the manner in which land was shaped was derived based on the climate and human adaptation to the specifics of the environment. Although they may not have thought about it in terms of science, people in early civilizations considered the "science of site" by understanding the hydrology, geology, vegetation, and wildlife and other microclimate factors in considering how the land was to be shaped. Geographers refer to this as environmental determinism. Development and construction through analysis of the local ecology, concepts of open space, protection of productive agricultural land, and management of stormwater and water quality are a part of sustainable design dialogue today that was well understood in early civilizations. Architects and engineers today have a wealth of information available on microclimate which must be leveraged in considering how land is to be shaped and buildings are to respond to (and shall we add, respect?) their environment. The NOAA Web site, www.weather.gov/climate provides access to information specific to any site in the United States, based on historical records, simply by inserting the site's longitude and latitude.

Environmental and green rating systems such as LEED, Green Globes, and Spirit acknowledge the importance of site development in sustainable design. Selection of the most appropriate site must consider many factors beyond simply economics. When viewed at the level of community, a project's location can minimize reliance on the automobile for transportation and support existing public transit infrastructure. Benefits include the avoidance of urban sprawl as well as the economic benefits of returning sites such as brownfields to productive use.

As land is shaped by humans in the early phases of development, erosion and sediment control have a significant impact on water and air quality.

Key LEED Site Principles

1. Protect farmland.
2. Develop only sites 5 feet above the floodplane.
3. Protect habitat for any species threatened: habitat preservation.
4. Avoid development within 100 feet of wetlands (we were tragically reminded of this in the aftermath of Hurricane Katrina along the U.S. Gulf coast).
5. Choose sites that have already been developed or are adjacent to existing development.
6. Minimize building footprints.
7. Share site amenities and open space.
8. Maintain density in urban areas as a way of preserving agricultural lands and greenfields for future generations as well as leveraging existing infrastructure for public transportation. Also reduce reliance on automobile use, with its associated environmental impacts.

Another hypothesis for this rise in temperature is that the presence of certain gases in the atmosphere is not allowing Earth to reflect enough of the heat energy from the sun back into space. Earth acts as a reflector to the sun's rays, receiving radiation from the sun, reflecting some of it into space (called *albedo*), and adsorbing the rest, only to reradiate this into space as heat. In effect, Earth

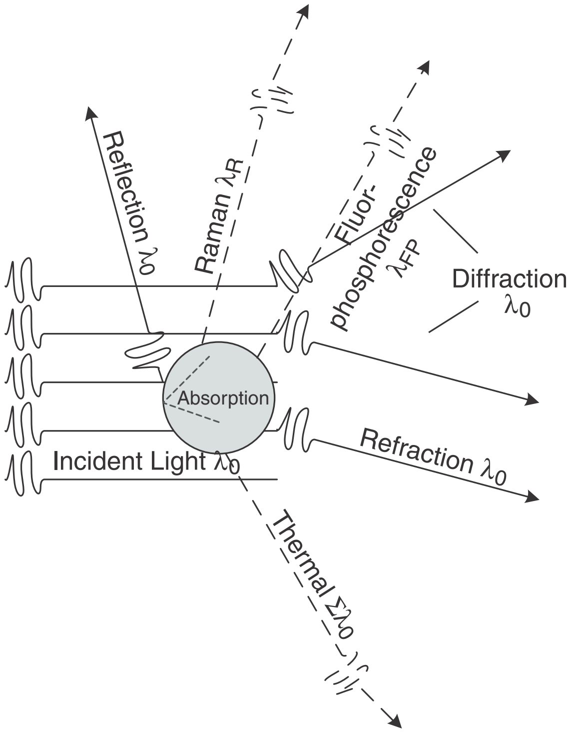


Figure 7.3 Patterns for heat and light energy.

acts as a wave converter, receiving high-energy high-frequency radiation from the sun and converting most of it into low-energy low-frequency heat to be radiated back into space. In this manner, Earth maintains a balance of temperature.

To better understand this balance, the light and heat energy have to be defined in terms of their radiation patterns, as shown in Figure 7.3. The incoming radiation (light) wavelength has a maximum at around 0.5 nm, and almost all of it is less than 3 nm. The heat energy spectrum (i.e., the energy reflected back into space) has a maximum at about 10 nm, almost all of it at a wavelength higher than 3 nm.

As both light and heat energy pass through Earth's atmosphere they encounter the aerosols and gases surrounding Earth. These can either allow the energy to pass through or can interrupt it by scattering or absorption. If the atoms in the gas molecules vibrate at the same frequency as the light energy, they will absorb the energy and not allow it to pass through. Aerosols will scatter the light and provide a "shade" for the Earth. This phenomenon is one of the reasons that scientists in the 1970s believed we were undergoing global cooling. That is, the combustion of coal and other fossil fuels releases sulfate aerosols which can scatter incoming solar radiation.

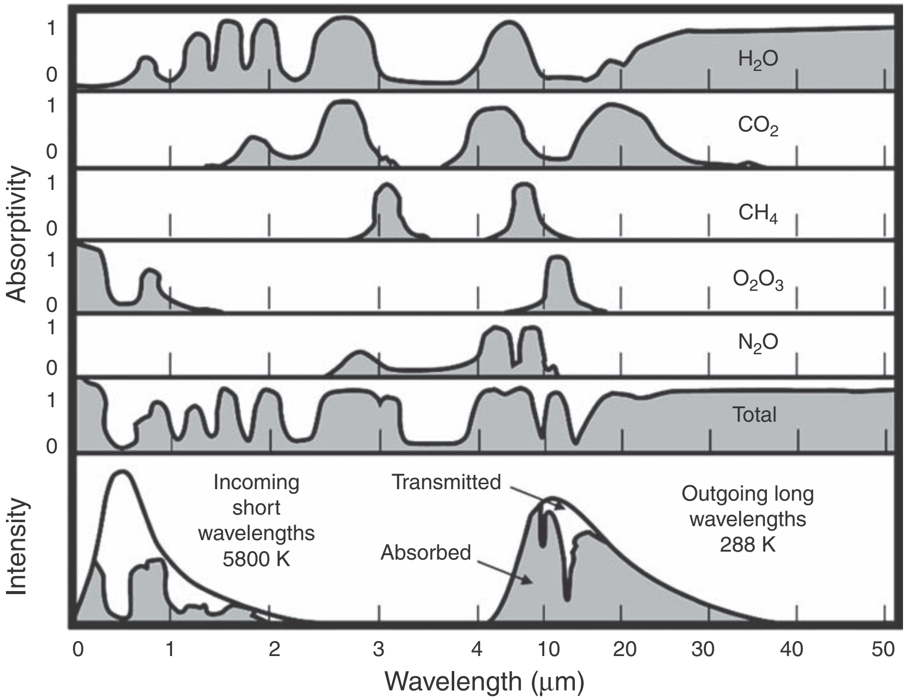


Figure 7.4 Adsorptive potentials of several important gases in the atmosphere. Also shown are spectra for the incoming solar energy and the outgoing thermal energy from Earth. Note that the wavelength scale changes at 4 μm.

From Gilbert Masters, *Introduction to Environmental Engineering and Science*, Prentice Hall, Upper Saddle River, NJ, 1998.

The absorptive potential of several important gases is shown in Figure 7.4, along with the spectra for the incoming light (short-wavelength) radiation and outgoing heat (long-wavelength) radiation. Incoming radiation is impeded by water vapor and oxygen and ozone. However, most of the light energy comes through unimpeded.

The heat energy reradiated from the Earth's surface, however, encounters several potential impediments. As it is trying to reach outer space, it finds that water vapor, CO_2, CH_4, O_3, and nitrous oxide (N_2O) all have absorptive wavelengths right in the middle of the heat spectrum. Quite obviously, an increase in the concentration of any of these will greatly limit the amount of heat transmitted into space. Appropriately, these gases are called *greenhouse gases* because their presence will limit the heat escaping into space, much as the glass of a greenhouse or the glass in your car limits the amount of heat that can escape, thus building up the temperature under the glass cover.

The effectiveness of a particular gas to promote global warming (or cooling, as is the case with aerosols) is known as *forcing*. The gases of most importance in forcing are listed in Table 7.3. Climate change results from natural internal processes and from external forcings. Both are affected by persistent changes in the composition of the atmosphere brought about by changes in land use, release of contaminants, and other human activities. *Radiative forcing*, the change

Table 7.3 Relative Forcing of Increased Global Temperature

Gas	Percent of Relative Radiative Forcing
Carbon dioxide, CO_2	64
Methane, CH_4	19
Halocarbons [predominantly chlorofluorocarbons (CFCs)]	11
Nitrous oxide, N_2O	6

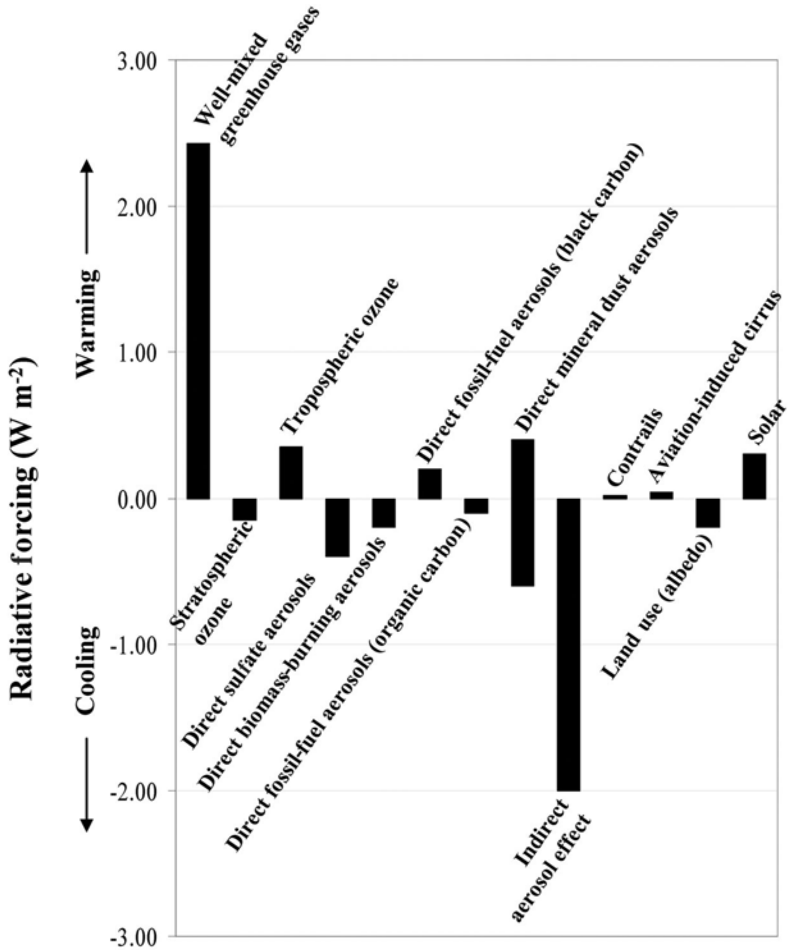


Figure 7.5 Global mean radiative forcing [watts per square meter (W m^{-2})] of the climate system for the year 2000 relative to 1750. The Intergovernmental Panel on Climate Change (IPCC) has applied a level of scientific understanding (LOSU) index to each forcing (see Table 7.3). This represents the panel's subjective judgment about the reliability of the forcing estimate, involving factors such as the assumptions necessary to evaluate the forcing, the degree of knowledge of the physical–chemical mechanisms determining the forcing, and the uncertainties surrounding the quantitative estimate of the forcing.

Data from Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis*, Chapter 6, IPCC, Geneva, Switzerland, 2001.

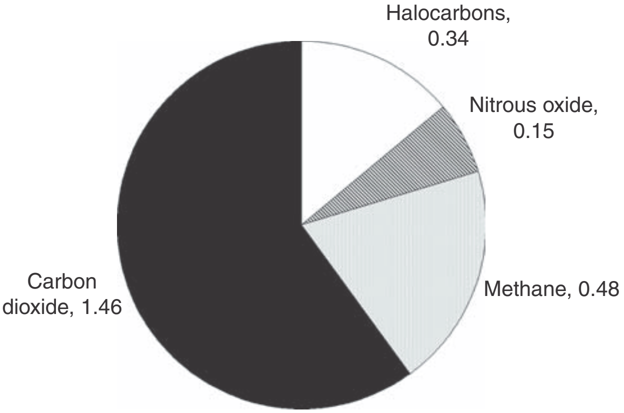


Figure 7.6 Relative contribution of well-mixed greenhouse gases to the $+2.43\ \mathrm{W\ m^{-2}}$ radiative forcing shown in Figure 7.6.

Data from: Intergovernmental Panel on Climate Change. *Climate Change 2001: The Scientific Basis*, Chapter 6, IPCC, Geneva, Switzerland, 2001.

in net vertical irradiance within the atmosphere, is often calculated after allowing stratospheric temperatures to readjust to radiative equilibrium while holding all tropospheric properties fixed at their unperturbed values. Commonly, radiative forcing is considered to be the extent to which injecting a unit of a greenhouse gas into the atmosphere changes global average temperature, but other factors can affect forcing, as shown in Figures 7.5 and 7.6. Note that these radiant gases include another family of carbon-based compounds, the halocarbons. The most notable halocarbons are the chlorofluorocarbons (CFCs), which are notorious for their destruction of the stratospheric ozone, but which are also greenhouse gases.

Sidebar: Applying the Synthovation/Regenerative Model: Ozone

Ozone is an example of the need to consider the combination of relevant factors: in this case, understanding the physics and chemistry of a situation. The term *smog* is a shorthand combination of "smoke–fog." However, it is really a code word for photochemical oxidant smog, the brown haze that can be seen when flying into Los Angeles and other metropolitan areas around the world. The fact is that to make smog, at least three ingredients are needed: light, hydrocarbons, and free radical sources such the oxides of nitrogen. Therefore, smog is found most often in the warmer months of the year, not because of temperature but because these are the months with greater amounts of sunlight. More sunlight is available for two reasons, both attributed to Earth's tilt on its axis. In the summer, Earth is tilted toward the sun, so the angle of inclination of sunlight is greater than when the sun is tipped away from Earth, leading to more intensity of light per Earth surface area. Also, daylight is longer in the summer.

Hydrocarbons come from many sources, but the fact that internal combustion engines burn gasoline, diesel fuel, and other mixtures of hydrocarbon makes them a ready source. Complete combustion results in carbon dioxide and water, but anything short of combustion will be a source of hydrocarbons, including some of the original hydrocarbons in the fuels, as well as new ones formed during combustion. The compounds that become free radicals, such as the oxides of nitrogen, are also readily available from internal combustion engines, since three-fourths of the troposphere is made up of molecular nitrogen (N_2). Although N_2 is not relatively chemically reactive, under the high-temperature, high-pressure conditions in an engine, it combines with the O_2 from the fuel–air mix to generate oxides that can provide electrons to the photochemical reactions.

Ozone is not always bad and is absolutely essential as a component of the stratosphere. The less O_3 there is in the stratosphere, the more harmful ultraviolet (UV) waves there are that find their way to Earth's surface. This illustrates that even though our exposure is to the physical insult (i.e., the UV), the exposure was brought about by chemical contamination. Chemicals released into the atmosphere, in turn, react with ozone in the stratosphere, decreasing the ozone concentration and increasing the amount of UV radiation at earth's surface. This has meant that the mean UV dose in the temperate zones of the world has increased, which has been associated with an increase in the incidence of skin cancer, especially the most virulent form, melanoma. Thus, to prevent this type of cancer requires a comprehensive viewpoint and an understanding of the complexity of the factors that have led to increased UV exposure.

There is much uncertainty about the effects of the presence of these radiant gases (see Table 7.4), but the overall effect of the composite of gases is well understood. The effectiveness of CO_2 as a global warming gas has been known for over 100 years. However, the first useful measurements of atmospheric CO_2 were not taken until 1957. The data from Mauna Loa show that even in the 1950s, the CO_2 concentration had increased from the baseline 280 ppm to 315 ppm; and this has continued to climb over the last 50 years at a nearly constant rate of about 1.6 ppm per year. The most serious problem with CO_2 is that the effects on global temperature are delayed due to its greenhouse effect. Even in the completely impossible scenario of not emitting any new CO_2 into the atmosphere, CO_2 concentrations will continue to increase from our present 370 ppm, with some estimates of possibly higher than 600 ppm.

Methane (CH_4) is the product of anaerobic decomposition and human food production. Methane is also emitted during the combustion of fossil fuels and the cutting and clearing of forests. The concentration of CH_4 in the atmosphere has been steady at about 0.75 ppm for over a thousand years, and then increased to 0.85 ppm in 1900. Since then, in only a hundred years, it has skyrocketed to 1.7 ppm. Methane is removed from the atmosphere by reaction with the

Table 7.4 Level of Scientific Understanding (LOSU) of Radiative Forcings

Forcing Phenomenon	LOSU
Well-mixed greenhouse gases	High
Stratospheric O_3	Medium
Tropospheric O_3	Medium
Direct sulfate aerosols	Low
Direct biomass-burning aerosols	Very low
Direct fossil-fuel aerosols (black carbon)	Very low
Direct fossil-fuel aerosols (organic carbon)	Very low
Direct mineral dust aerosols	Very low
Indirect aerosol effect	Very low
Contrails	Very low
Aviation-induced cirrus	Very low
Land use (albedo)	Very low
Solar	Very low

Source: Intergovernmental Panel on climate change, *Climate Change 2001: The Scientific Basis*, Chapter 6, IPCC, Geneva, Switzerland, 2001.

hydroxyl radical (OH):

$$CH_4 + OH + 9O_2 \rightarrow \underset{\text{Carbon Dioxide}}{\underset{\downarrow}{CO_2}} + 0.5H_2 + \overset{\text{Water Vapor}}{\overset{\downarrow}{2H_2O}} + \underset{\text{Ozone}}{\underset{\downarrow}{5O_3}}$$

This indicates that the reaction creates carbon dioxide, water vapor, and ozone, all of which are greenhouse gases, so the effect of one molecule of methane is devastating in its production of gases that contribute to the greenhouse effect.

Halocarbons, the chemical class linked to the destruction of stratospheric ozone, are also radiant gases. The most effective global-warming gases are CFC-11 and CFC-12, both of which are no longer manufactured, and the banning of these substances has shown a leveling off in the stratosphere. Nitrous oxide is also in the atmosphere mostly as a result of human activities, especially the cutting and clearing of tropical forests. The greatest problem with nitrous oxide is that there appear to be no natural removal processes for this gas, so its residence time in the stratosphere is quite long.

The net effect of these global pollutants is still being debated. Various atmospheric models used to predict temperature change over the next hundred years vary widely. They nevertheless agree that some warnings will occur even if we do something drastic today. By the year 2100, even if we do not increase our production of greenhouse gases and if the United States takes actions similar to those of the Kyoto Accord, which encourages a reduction in greenhouse gas production, the global temperature is likely to be between 0.5 and 1.5°C warmer.

CARBON SEQUESTRATION

One of the most frustrating aspects of the global climate change debate is the seeming paucity of ways to deal with the problem, and the discussions seem to be very polarized. Can anything be done to ameliorate the increase in carbon being released to the atmosphere? Actually, one promising area involves sequestration.

We can approach sequestration from two perspectives. First, it is an ongoing process on Earth. The arrows in Figure 7.1 show that carbon compounds, especially CO_2 and CH_4, find their way to the ocean, forests, and other carbon sinks. Like many geobiochemical processes, sequestration can be influenced by human activity. Thus, there is a conservation aspect to protecting these mechanisms that are working to our benefit.

The second approach is one that is most familiar to the engineer; that is, we can apply scientific principles to enhance sequestration. The sequestration technologies include new ways either to sequester carbon or to enhance or expedite processes that already exist.

Conservation is an example of a more "passive" approach. There are currently enormous releases of carbon that, if eliminated, would greatly reduce loading to the troposphere. For example, anything we can do to protect the loss of forest, woodlands, wetlands, and other ecosystems is a way of preventing future problems. In fact, a high percentage of the terrestrial fluxes and sinks of carbon involves the soil. Keeping the soil in place must be part of the overall global strategy to reduce greenhouse gases (see the discussion box "Soil: Beyond Sustainable Sites").

Soil: Beyond Sustainable Sites

Good design requires an understanding of soil. Design professionals are often principally concerned with soil mechanics, particularly such aspects as gel strength and stability, so that it serves as a sufficient underpinning for structural foundations and footing. They are also concerned about drainage, compaction, shrink–swell characteristics, and other features that may affect building site selection. More recently, green building programs have included soils as part of the overall strategy. This is a valuable first step, but the value of soils goes beyond the sustainability of an individual building site.

SOIL's VALUE

Soil is classified into various types. For many decades, soil scientists have struggled with uniformity in the classification and taxonomy of soil. Much of the rich history and foundation of soil scientists has been associated with agricultural productivity. The very essence of a soil's "value" has been its capacity to support plant life, especially crops. Even forest soil knowledge owes much to the agricultural perspective, since much of the reason for investing in forests has been monetary. A stand of trees is seen by many to be a *standing crop*. In the United States, for example, the Forest Service is an agency of the U.S. Department of Agriculture. Engineers have been concerned about the statics and dynamics of soil systems, improving the understanding of soil mechanics so that they may support, literally and figuratively, the built environment. The agricultural and engineering perspectives have provided valuable information about soil that environmental professionals can put to use. The information is certainly necessary, but not completely sufficient, to an understanding of how pollutants move through soils, how the soils themselves are affected by the pollutants (e.g., loss of productivity, diversity of soil microbes), and how soils and contaminants interact chemically (e.g., changes in soil pH change the chemical and biochemical transformation of organic compounds). At a minimum, environmental scientists must understand and classify soils according to their texture or grain size (see Table B7.1), ion-exchange capacities, ionic strength, pH, microbial populations, and soil organic matter content. These factors are crucial to green design.

Table B7.1 Commonly Used Soil Texture Classifications

Name	Size Range (mm)
Gravel	> 2.0
Very coarse sand	1.0–1.999
Coarse sand	0.500–0.999
Medium sand	0.250–0.499
Fine sand	0.100–0.249
Very fine sand	0.050–0.099
Silt	0.002–0.049
Clay	< 0.002

Source: T. Loxnachar, K. Brown, T. Cooper, and M. Milford, Sustaining Our Soils and Society, American Geological Institute, Soil Science Society of America, USDA Natural Resource Conservation Service, Washington, DC, 1999.

Whereas air and water are fluids, sediment is a lot like soil in that it is a matrix made up of various components, including organic matter and unconsolidated material. The matrix contains liquids (*substrate* to the chemist and engineer) within its interstices. Much of the substrate of this matrix is water, with varying amounts of solutes. At least for most environmental conditions, air and water are solutions of very dilute amounts of compounds. For example, air's solutes represent small percentages of the solution at the highest concentrations (e.g., water vapor), and most other solutes represent parts per million (greater than 300 ppm of carbon dioxide). Thankfully, most contaminants in air and water, if found at all are found in the parts per billion range. On the other hand, soil and sediment themselves are conglomerations of all states of matter. Soil is predominantly solid but frequently has large fractions of liquid (soil water) and gas (soil air, methane, carbon dioxide) that make up the matrix. The composition of each fraction is highly variable. For example, soil gas concentrations are different from those in the atmosphere and change profoundly with depth from the surface. Table B7.2 illustrates the inverse relationship between carbon dioxide and molecular oxygen. Sediment is really an underwater soil. It is a collection of particles that have settled on the bottom of water bodies.

Table B7.2 Composition (Percent Volume of Air) of Two Important Gases in Soil Air

	Silty Clay		Silty Clay Loam		Sandy Loam	
Depth from Surface (cm)	O_2	CO_2	O_2	CO_2	O_2	CO_2
30	18.2	1.7	19.8	1.0	19.9	0.8
61	16.7	2.8	17.9	3.2	19.4	1.3
91	15.6	3.7	16.8	4.6	19.1	1.5
122	12.3	7.9	16.0	6.2	18.3	2.1
152	8.8	10.6	15.3	7.1	17.9	2.7
183	4.6	10.3	14.8	7.0	17.5	3.0

Source: V. P. *Evangelou, Environmental Soil and Water Chemistry: Principles and Applications*, Wiley, New York, 1998.

Ecosystems are combinations of these media. For example, a wetland system consists of plants that grow in soil, sediment, and water. The water flows through living and nonliving materials. Microbial populations live in the surface water, with aerobic species congregating near the water surface and anaerobic microbes increasing with depth due to the decrease in oxygen levels resulting from the reduced conditions. Air is important not only at the water and soil interfaces, but is a vehicle for nutrients and contaminants delivered to the wetland. The groundwater is fed by the surface water during high-water conditions and feeds the wetland during low-water conditions.

So another way to think about these environmental media is that they are compartments, each with boundary conditions, kinetics, and partitioning relationships within a compartment or among other compartments. Chemicals, whether nutrients or contaminants, change as a result of the time spent in each compartment. The designer's challenge is to describe, characterize, and predict the behaviors of various chemical species as they move through media in a way that makes best use of them. When something is amiss, the cause and cure lie within the physics, chemistry, and biology of the system. It is up to the designer to apply the principles properly.

CARBON SEQUESTRATION IN SOIL

When tallying the benefits of soil conservation, a few always come to mind, especially soil's role in sustainable agriculture and food production, keeping soil from becoming a pollutant in the surface waters, and its ability to sieve and filter pollutants that would otherwise end up in drinking water. However, another, less obvious benefit is as a sink for carbon. Soil is lost when land is degraded by deforestation and as a result of inadequate land use and management in sensitive soil systems, especially those in the tropics and subtropics, such as slash-and-burn and other aggressive practices. As is often the case in ecosystems, some of the most valuable ecosystems in terms of the amount of carbon sequestered and oxygen generated are also the most sensitive. Tropical systems, for example, often have some of the least resilient soils, due to the rapid oxidation processes that take place in humid, oxidized environments.

Sensitive systems are often given value by a society for a single purpose. Bauxite, for example, is present in tropical soils due to the physical and chemical conditions of the tropics (aluminum in parent-rock material, oxidation, humidity, and ion-exchange processes). However, from a life-cycle and resource planning perspective, such single-mindedness is folly. The decision to extract bauxite, iron, or other materials from sensitive tropical rain forests must be seen in terms of local, regional, and global impacts. With this in mind, international organizations promote improved land-use systems and land management practices that provide both economic and environmental benefits.

Keeping soil intact protects biological diversity, improves ecosystem conditions, and increases carbon sequestration. This last-mentioned benefit includes numerous forms of carbon in all physical phases. As discussed and shown in Table B7.2, soil gases include CO_2 and CH_4. Plant root systems, fungi, and other organisms comprised of amino acids, proteins, carbohydrates, and other organic compounds live in the soil. Even inorganic forms of carbon are held in soil, such as the carbonate, bicarbonate, and carbonic acid chemical species in soils resulting from chemical reactions with parent-rock material, especially limestone and dolomite.

When the soils are lost, all of these carbon compounds become available to be released to the atmosphere in the form of greenhouse gases.

The principal biological process at work in these systems is photosynthesis, whereby atmospheric CO_2 is transformed to molecular oxygen by way of the plant's manufacturing biomass (see the discussion box: Photosynthesis: Nature's Green Chemistry). When photosynthesis stops, less CO_2 is extracted from the environment and less carbon is stored in the soil. For example, much of the biomass of a tree is in its root systems (more than half for many species). When the tree is cut down, not only does the harvested biomass release carbon, such as in the smoke when the wood is burned, but gradually the underground stores of carbon in the root systems migrate from the soil to the troposphere (see the discussion box: The Tree).

Photosynthesis: Nature's Green Chemistry

Organic material generated when plants and animals use stored solar energy is known as *biomass*. Photosynthesis is the process by which green plants* absorb the sun's energy, convert it to chemical energy, and store the energy in the bonds of sugar molecules. The process of photosynthesis takes place in the chloroplasts, which are organelles (*chloro* = green; *plasti* = formed, molded), using the green pigment chlorophyll (*chloro* = green; *phyll* = leaf), which has a porphyrin ring with magnesium in the center.

The simplest sugars are monosaccharides, which have the molecular formula $(CH_2O)_n$, where n may be any integer from 3 to 8. Monosaccharides contain hydroxyl groups and either a ketone or an aldehyde group (see the discussion of organic chemistry earlier in the Chapter). These functional groups are polar, rendering sugars very soluble in water. Fructose has the same molecular formula as glucose, but the atoms of carbon, hydrogen, and oxygen are arranged a little differently (i.e., they are isomers). Glucose has an aldehyde group; fructose has a ketone group. This structural nuance imparts different physical and chemical properties to the two monosaccharides.

These monosaccharides link by a dehydration synthesis reaction to form disaccharides, forming one water molecule in the process. Maltose is formed by joining two glucose molecules. Sucrose is formed by combining glucose and fructose. Lactose is formed by combining glucose and the monosaccharide galactose. Maltose, sucrose, and lactose have the same molecular formula, $C_{12}H_{22}O_{11}$, but are each isomers with unique physical and chemical properties.

The energy in these sugars' chemical bonds moves through the food web, being passed on to animals that consume the plants. Although numerous chemical reactions occur in photosynthesis, the process can be seen a very simple reaction with water and carbon dioxide reacting in the presence of radiant energy to form sugars (e.g., glucose) and molecular oxygen:

$$6H_2O + 6CO_2(+\text{radiant energy}) \rightarrow C_6H_{12}O_6 + 6O_2$$

* In fact, photosynthesis occurs in two taxonomical kingdoms: Plantae and Protista (Protoctista). Algae fall in the latter kingdom.

Thus, biomass is a renewable energy source since it will be available as long as green plants can be grown. Biomass energy has been produced from woody plants, herbaceous plants, manure, and solid wastes. When biomass is burned, the process of combustion releases the stored chemical energy as heat. The biomass can be combusted directly in a wood-burning fireplace or a

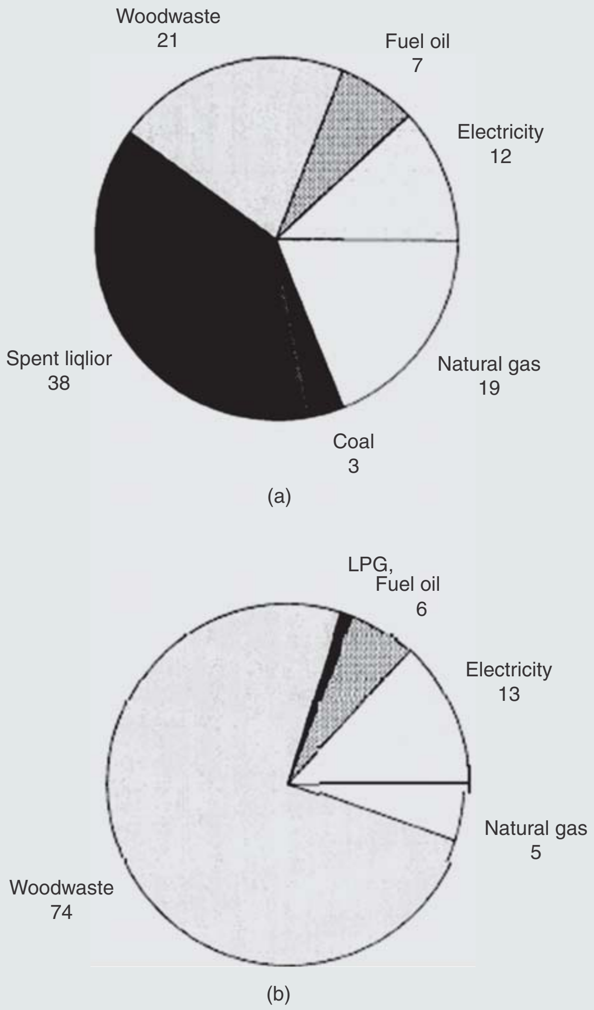


Figure B7.1 Fuel sources for the (a) paper and (b) pulp industries. Biomass fuel, represented by wood waste and spent liquor, make up the majority of end-use consumed energy, with, 60 to 75% from biomass.

From Energy Information Administration, *Estimates of U.S. Biofuels Consumption 1989,* U.S. Department of Energy, Washington, DC, April 1991.

large-scale biomass electricity-generating station. The industrial sector uses about one-third of the primary energy in the United States. Wood as a fuel source makes up approximately 8% of total industrial primary energy use. Most of this is in the pulp and paper industry, where wood and its by-products are readily available (see Fig. B7.1). It must be noted that conservation must be factored into the life-cycle assessment for these processes. For example, we have compared paper and pulp fuel uses; however, if society can find more "paperless" systems, such as electronic documentation, the demand for such wood-based products would also drop. This could be accompanied by less tree-cutting in the first place, with the advantage of keeping the tree systems intact and preserving the present sequestration of carbon.

Certainly, numerous industrial sectors can put the process of photosynthesis to work to find renewable and sustainable feedstocks. Arguably, those most heavily invested in nonrenewable resources have the most to gain by moving to renewable resources.*

* U.S. Congress, Office of Technology Assessment, "Potential environmental impacts of bioenergy crop production," Background Paper, OTA-BP-E-118, U.S. Government Printing Office, Washington, DC, September 1993.

The Tree

Building and landscape architecture draw increasingly on living resources as part of good design. Thus, buildings must be incorporated within the various scales of ecosystems. All ecosystems are comprised of a harmony of abiotic and biotic components. The relationships of organisms to one another and to the abiotic environment are cyclical.

Green engineering is all about applying knowledge about life cycles. A good decision early in the life cycle makes for acceptable outcomes. A poor decision leads to artifacts that will have to be addressed. Pollution prevention is preferable to pollution abatement. Nature provides some excellent analogs of how to view a life cycle. One of the best is the tree.

Sometimes, the things that we are most familiar with are the most difficult to define. The tree is one of these. First, most of us have a working definition of a tree. Most would agree that a tree is woody; it is a plant with persistent woody parts that do not die back in adverse conditions. Most woody plants are trees or shrubs. Usually, the only distinction between a tree and a shrub is that the shrub is low-growing, usually less than 5 m tall. Usually, it also has more stems and may have a suckering growth habit, although many trees also have this habit (e.g., a river birch, *Betula nigra*, can have multiple trunks and a suckering habit). Trees and shrubs differ from most herbs in structure.

Woody plants have connecting systems that link modules together and that connect the modules to the root system. These connecting systems do not rot away after the growing season. In fact, for years a tree thickens these connecting tissues. Actually, most of the mass of a woody tree is dead, with only a thin layer of living tissue below the bark. However, this living stratum regenerates

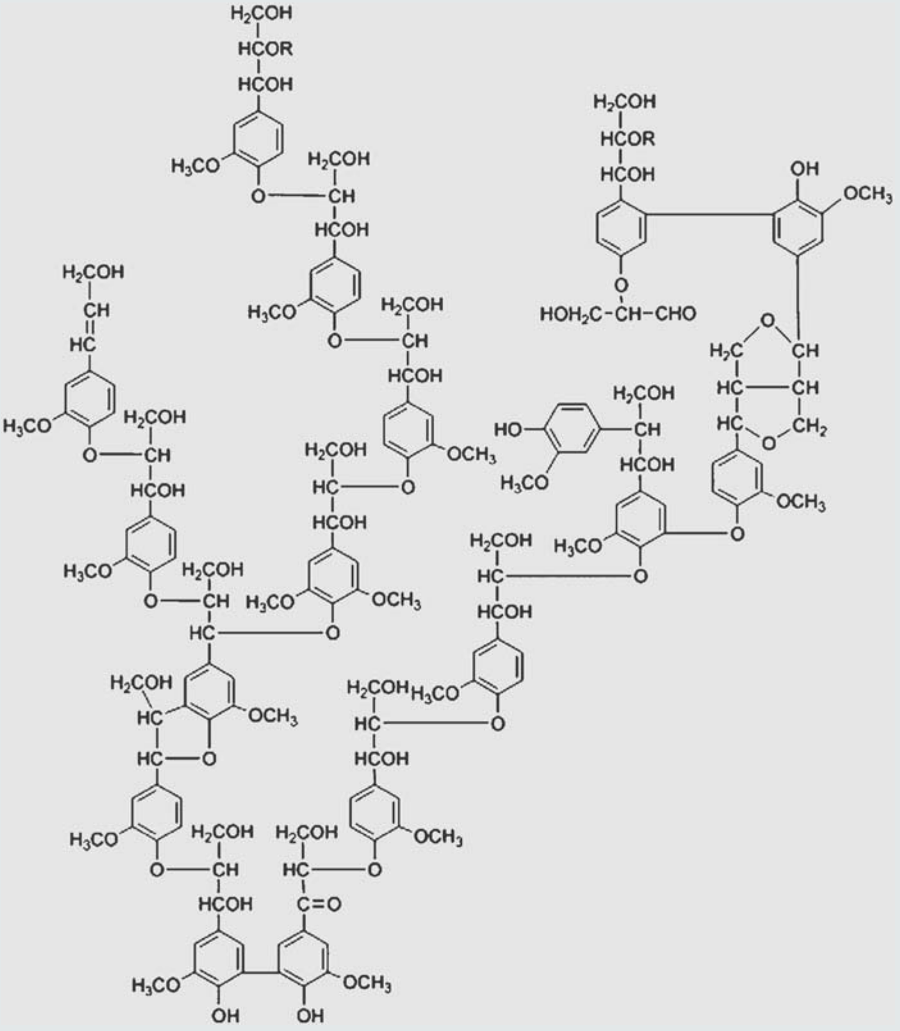


Figure B7.2 Configuration of a lignin polymer.

From Institute of Biotechnology and Drug Research, *Environmental Biotechnology and Enzymes*, IBDR, Kaiserslautern, Germany. Adapted from E. Adler, "Lignin chemistry:past, present and future," *Wood Science Technology*, 11, 169–218, 1977.

continuously, adding layers after each growing season. This process makes the tree rings. Trees receive nutrients from soil via roots and from air via leaves. The leaves also absorb light energy needed for photosynthesis. So the tree is a system of living and dead tissue, both absolutely necessary for structure and function.

All plants contain cellulose, but woody plants also contain lignin. Both cellulose and lignin are polymers, which are large organic molecules comprised of repeated subunits (i.e., monomers). Lignin is the "glue" that holds the tree's biochemical system together. The monomers that comprise lignin polymers can vary depending on the sugars from which they are derived. In fact, lignins have so many random couplings that the exact chemical structure is seldom known. One configuration of the lignin molecule is shown in Figure B7.2.

Lignin fills the spaces in a woody plant's cell wall between cellulose and two other compounds, hemicellulose and pectin. Lignin accounts for the rigidity of wood cells and the structural integrity and strength of wood by its covalent bonds to hemicellulose and cross-linking to polysaccharides.

TREES AS AN ENERGY SOURCE

Both herbaceous and woody plants can serve as *bioenergy crops*, which include annual row crops such as corn, herbaceous perennial grasses [known as herbaceous energy crops (HECs)] and trees. One of the most prominently mentioned HECs is switchgrass (*Panicum virgatum*), a hardy, perennial rhizomatous grass that is among the dominant tall grass prairies species in the high plains of North America. Bioenergy crops also include fast-growing shrubs and trees, known as *short-rotation woody crops* (SRWCs), such as poplar. SRWCs typically consist of a single-genus plantations of closely spaced (2 to 3 m apart on a grid) trees that are harvested on a 3- to 10-year cycle. Regeneration is an important selection criterion for bioenergy species. HECs must regrow from the remaining stubble, and SRWCs must regrow from the remaining stumps.* The harvests can continue for two decades or more. Pesticides, fertilizer, and other soil enhancements may be needed, but the farming does not differ substantially from that typical of growing ordinary crops.

Both the cellulose and lignin have heat values; thus, these crops are known as *lignocellulosic energy crops*. The feedstocks of HECs and SRWCs may be used directly to generate electricity or can be converted to liquid fuels or combustible gases.

* U.S. Congress, Office of Technology Assessment, "*Potential environmental impacts of bioenergy crop production,*" Background Paper, OTA-BP-E-118, U.S. Government Printing Office, Washington, DC, September 1993.

The Forest System

A tree represents a system within a system. It can be part of a forest ecosystem, where it depends on nutrients provided by the air and soil. The soil receives its nutrients through abiotic and biotic processes, such as nitrates from lightning, nitrogen-fixing bacteria in legumes' root nodules, and the breakdown of detritus by aerobes and anaerobes on the forest floor. The nitrogen cycle is quite complex (see Fig. B7.3). Basically, numerous simultaneous chemical reactions are taking place, so the forest ecosystem is a balance of various chemical forms of nitrogen (and phosphorus, sulfur, and carbon, for that matter). The chemical reactions in a nutrient cycle consist of biochemical processes whereby organisms take simpler nitrogen compounds, including microbial fixation of molecular nitrogen (N_2) from the atmosphere and form amino acids in the tissues of plants and animals. In the opposite direction, mineralization is the process by which organic matter is reduced or oxidized to mineral forms, such as ammonia, ammonium hydroxide, nitrite, and nitrate. Note that the gases at the top of the figure include those that are important in air pollution. For example, NO is one of the compounds involved in the photochemistry that leads to formation of the pollutant ozone (O_3) in the troposphere. Note also

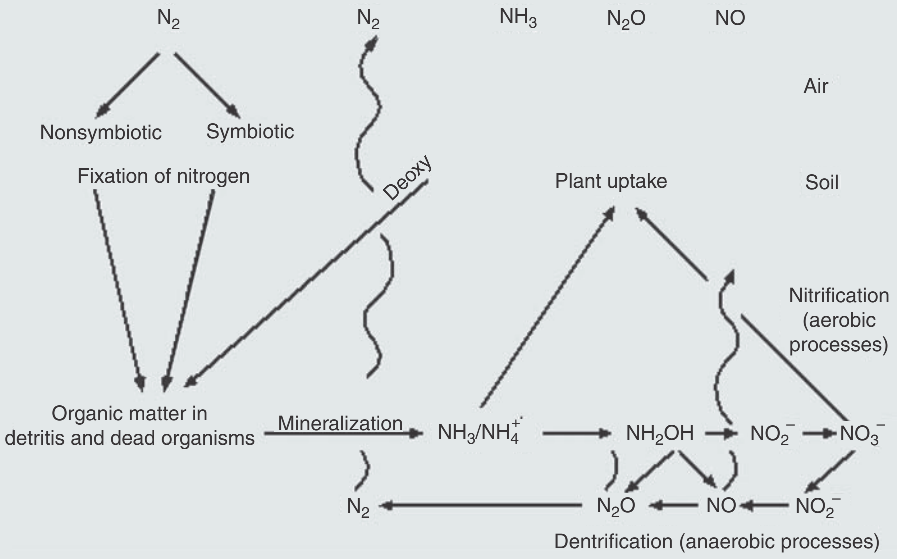


Figure B7.3 Nitrogen cycling in a forest ecosystem.

From D. A. Vallero, *Environmental Contaminants: Assessment and Control*, Elsevier Academic Press, Burlington, MA, 2004.

that trees are central in the figure. At their base is detritus, where microbes are breaking down complex molecules. Nutrients in the soil are transported to the tree's cells by the roots' capillary action, and gases are transpired through leaves back to the atmosphere.

NUTRIENT LOSS

Trees play an important role in holding nutrients in sinks. Nitrate can be a good indicator of nutrient loss in an ecosystem (see Table B7.3). Combinations of trees and ground cover can result in significantly different nutrient loss than that from trees alone. One recent study indicated that considerably higher losses of nitrate occur early in the growing season in row crops than in tree plots. With time, the nitrate loss in these plots was reduced to levels similar to that in tree plots. Similar results were obtained with ammonium nitrate and phosphorus losses and are explained by the fertilization regimen.*

Table B7.3 Average Nitrate Loss (g ha^{-1}) for Five Selected Months by Plant Cover from Limestone Valleys of the Tennessee Valley Region[a]

			Trees	
Month	Corn	Switchgrass	Without Cover Crop	With Cover Crop
May	275	477	1	41
July	4	44	9	2
September	1	0	11	3
November	5	12	1	0
January	6	0	2	0

[a] The soils are moderately to severely eroded Decatur silty clay loam, undulating phase, with slopes averaging 2.5 to 3%. The area has been under cultivation for at least the past 15 years.

Table B7.3 also demonstrates the diversity of plants in nutrient storage. However, growing trees may not provide the initial protection expected previously. If erosion protection is required, the use of either switchgrass or trees with cover crops is recommended. Trees can be grown successfully with a cover crop between the rows if care is taken to keep the tree row itself free

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* T. H. Green, G. F. Brown, L. Bingham, D. Mays, K. Sistani, J. D. Joslin, B. R. Bock, F. C. Thornton, and V. R. Tolbert, "Environmental impacts of conversion of cropland to biomass production," *Proceedings of the 7th National Bioenergy Conference: Partnerships to Develop and Apply Biomass Technologies*, Nashville, TN, September 15–20, 1996. Note that both corn and switchgrass plots were fertilized the first year, while fertilization of the tree plots was delayed until the second year.

of weeds. For example, planting leguminous cover crops under sycamore trees (*Platanus occidentalis*) in plantations during the second growing season has been shown to increase tree growth during subsequent year.* This particular study indicates that the use of cover crops during the establishment phase is a workable alternative for SRWC production. The researchers have indicated that more study is needed to see which cover plant best reduces erosion in SRWC plantations while causing the least growth reduction.

The tree is also part of the two most important biogeochemical processes on earth: ion exchange and photosynthesis (see the discussion box: Photosynthesis: Nature's Green Chemistry). Ion exchange is actually an example of sorption: that is, movement of a chemical species from the liquid or gas phase to the solid phase. (Movement of a chemical species from the solid to, liquid phase is *dissolution*. Movement from the solid phase to the gas phase is *volatilization*.) So the tree grows and thrives as a function of available nutrients and other cycles within the forest ecosystem. But it can also be part of systems other than a forest, such as your yard. As in the forest, the tree is part of a complex balance among grass, shrubs, annuals, and compost and other decomposing materials in the soil.

* S. G. Haines, L. W. Haines, and G. White, "Leguminous plants increase sycamore growth in northern Alabama," *Soil Science Society of America Journal*, 42; 130–132, 1978.

"GREEN" TREES

The tree is a central feature of green design. For example, the choice of wood as a material affects the sustainability of a structure. Standards such as LEED recognize that the life-cycle costs for local genera are preferable to distant species since trees are heavy and expensive to ship. Also, certain species are rapid growers and replenish the biomass much faster than do others. Bamboo is an example of a quick-growing, easily harvested genus. Decisions about trees must also consider greenhouse gas balances. Trees' extensive root systems account for most of the biomass of many tree species. Many coniferous trees (e.g., pines) cannot survive if they are cut too far down the trunk, whereas many deciduous trees will grow back readily after top-harvesting. So, for example, a maple stand may be harvested repeatedly for wood, whereas pines must be replanted.

"Active" approaches include the application of technologies to send carbon to the sinks, including deep rock formations and the oceans. Such technology can be applied directly to sources. For example, fires from China's coal mines presently release about 1 billion metric tons of CO_2 to the atmosphere every

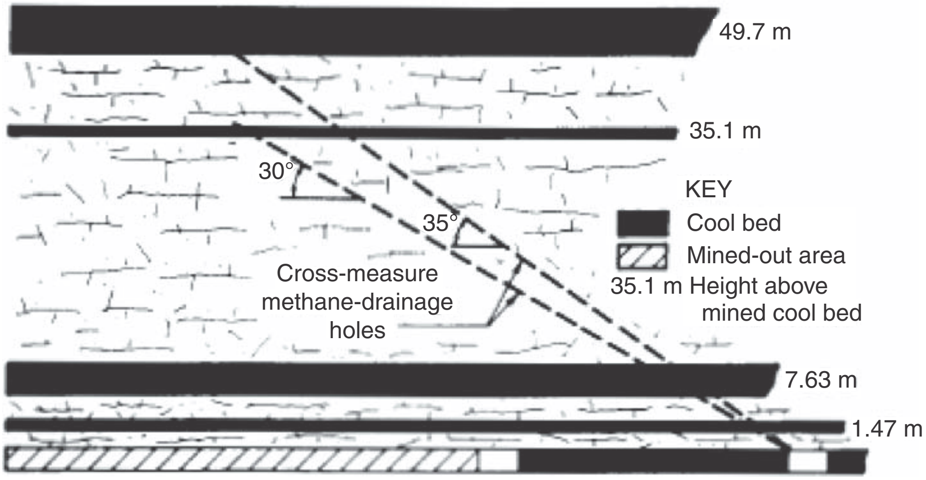


Figure 7.7 Sectional view of cross-measure methane-drainage holes in a coal mine ventilation system.

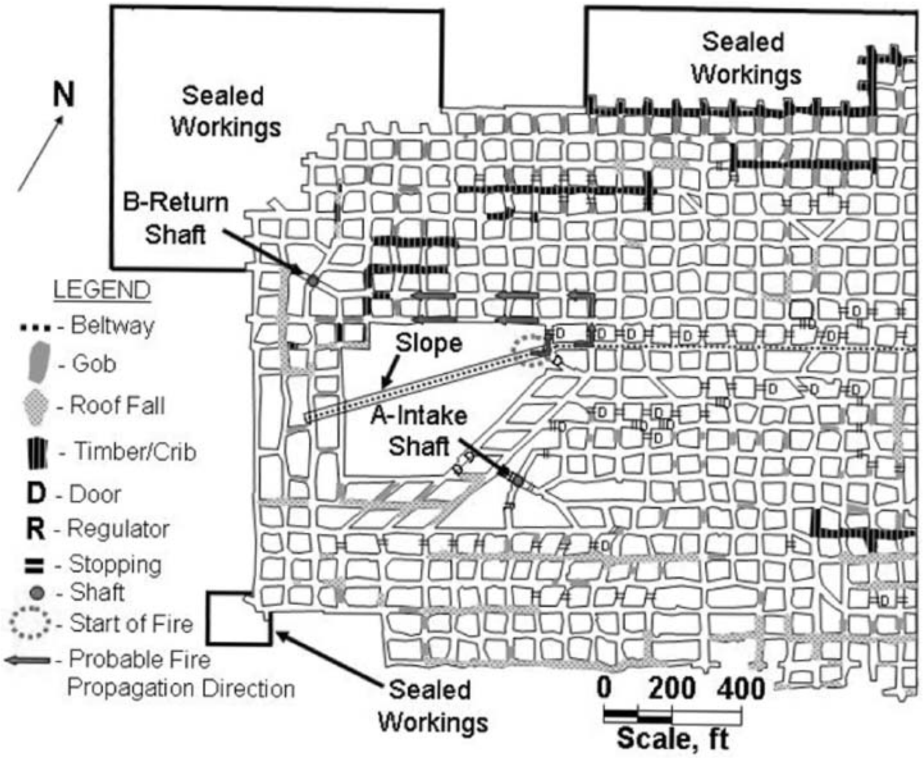
From A. C. Smith, W. P. Diamond, and J. A. Organiscak, "Bleederless ventilation systems as a spontaneous combustion control measure in U.S. coal mines," Information Circular 9377, NTIS PB94-152816, U.S. Department of the Interior, Bureau of Mines, Washington, DC, 1994; B. R. McKensey and J. W. Rennie, "Longwall ventilation with methane and spontaneous combustion: Pacific Colliery," *Proceedings of the 4th International Mine Ventilation Congress*, Brisbane, Australia, July 3–6, 1988, Australia Institute of Mining and Metals, Melbourne, Australia, 1988, pp. 617–624.

year. Estimates put India's coal mine fire releases to be about 50 million metric tons. This accounts for as much as 1% of all carbon greenhouse releases. This is about the same as the CO_2 released by all the gasoline-fuel automobiles in the United States. Engineering solutions that reduce these emissions would actively improve the net greenhouse gas global flux.

The United States has a checkered history when it comes to coal mine fires. Some have burned for more than a century. Intuitively, putting out such fires may seem straightforward. For example, we know that combustion depends on three components: a fuel, a heat source, and oxygen. All three are needed, so *all* we have to do to smother a coal fire is to eliminate one of these essential ingredients. Unfortunately, since the fire is in an underground vein, fuel is plentiful. Actually, the solid-phase coal is less of a factor than the available CH_4, which is ubiquitous in coal mines. And like the "whack-a-mole" game, the avenues of access to the fire mean that the heat source is available in different channels. When one is closed off, another appears.

So that leaves us with depriving the fire of O_2. This is much easier said than done. In fact, engineering has been an outright failure in this regard. Flooding the mines is ineffective, since the fire simply finds alternative pathways in the leaky underground strata. Excavation has to be almost 100% to be effective. Flushing with slurries has the same problems. In fact, miner safety and postignition fire suppression can be seen as competing factors in mining. To ensure sufficient oxygen levels and low toxic gas concentrations, a mine's ventilation system requires methane-drainage holes to control methane at the face. In many abandoned mines, cross-measure holes (see Fig. 7.7) were the most common types. These systems are one reason that oxygen remains available to a fire.[3]

Figure 7.8 Map of the fire zone in the Excel No. 3 coal mine in eastern Kentucky.



However, there is promise. Recent studies have shown that certain foams can deprive fires of O_2 over extensive areas. For example, a study sanctioned by the U.S. National Institute of Occupational Safety and Health (NIOSH) showed preliminary success in sealing a coal mine from oxygen inflow and suppression of the fire with liquid nitrogen and gas-enhanced foam.[4] The technology needs to be advanced to address very large fires. The fire studied by NIOSH (see Fig. 7.8) was caught in the early stages and suppressed within two weeks. But like many engineering prototypes, showing that it *can* work is the first step to ensureing that it *will* work.

Another active engineering approach is an enhancement of existing processes. For example, in addition to conserving present levels of carbon sequestration, technologies can be adapted to *increase* the rates of sequestration. Every sink shown in Figure 7.7 is a candidate. The scale of such technology can range from an individual source (see Fig. 7.9), such as a fossil-fuel-burning electricity generation station that returns its stack gases to an underground rock stratum, to an extensive system of collection and injection systems that includes an entire network of facilities. A combination of disincentives such as carbon taxes and application of emerging technologies can decrease the carbon flux to the

Figure 7.9 Carbon dioxide that is produced at the Sleipner natural gas complex off the coast of Norway is removed and pumped into the Utsira Formation, a highly permeable sandstone. In this case, the sequestration cost is less than the Norwegian carbon emission tax. Courtesy of Øyvind Hagen, Statoil.

atmosphere. Thus, green engineering is part of an overall comprehensive geopolitical strategy.

Even a system as large as the ocean has its limits in greenhouse gas sequestration. For starters, most of the CO_2 generated by human activities (i.e., anthropogenic) resides in the upper layers of the ocean (see Fig. 7.10). Carbon compounds move into and out of oceans predominantly as a function of the solubility of the compound and water temperature. For CO_2, this means that more of the compound will remain in the ocean water with decreasing temperature. Ocean mixing is very slow. Thus, the anthropogenic CO_2 from the atmosphere is confined predominantly to the very top layers. Virtually half of the anthropogenic CO_2 taken up by the ocean for the previous two centuries has stayed in the upper 10% of the ocean. The ocean has removed 48% of the CO_2 released to the troposphere from burning fossil fuels and cement manufacturing.[5]

Thus, to keep CO_2 sequestered, one factor is to help it find its way to the cooler, deeper parts of the ocean. When it resides near the warmer surface, it is more likely to be released to the atmosphere. The actual mass of carbon can be increased by management. For example, certain species of plankton are often limited in growth by metals, especially iron. Thus, increasing the iron concentrations in certain ocean layers could dramatically increase the ability of these organisms to take up and store carbon. Obviously, any large-scale endeavor like this must be approached with appropriate caution. Too often, the cure can

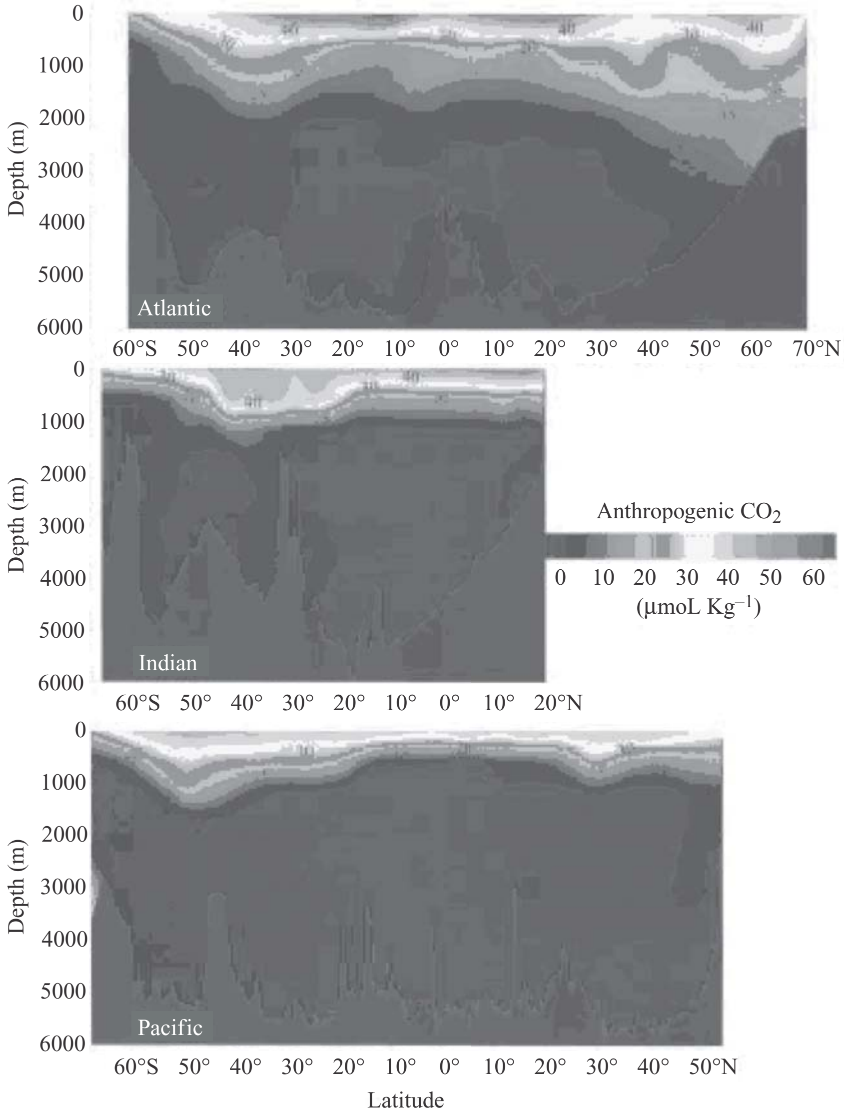


Figure 7.10 Anthropogenic carbon concentrations in three ocean systems. Note that most of the CO_2 resides above the 1000-m depth.

From the global CO_2 survey by the National Oceanic and Atmospheric Administration, and R. A. Feely, C. L. Sabine, T. Takahashi, and R. Wanninkhof, "Uptake and storage of carbon dioxide in the ocean: the global CO_2 survey," *Oceanography*, 14(4), 18–32 (2001).

be worse from the disease. Adding iron could certainly adversely affect other parts of the ocean ecosystems. The best decisions are those that account for all possible outcomes, certainly not those hoped for. Such an approach would probably include tests in laboratories, stepped up to prototypes on as many possible scenarios and species possible, before actual implementation.

The entire area of enhanced carbon sequestration is very promising. Figure 7.11 shows a number of venues in which this green engineering approach

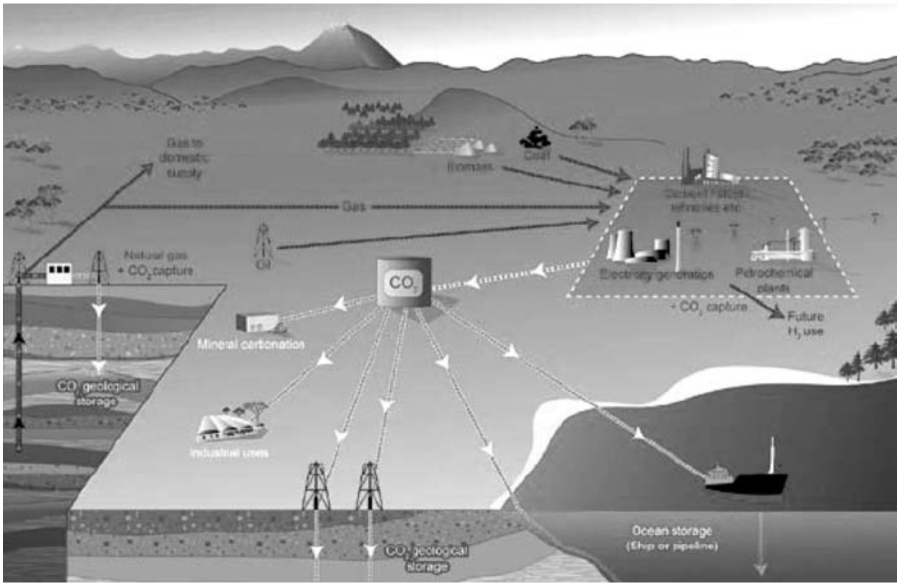


Figure 7.11 Potential application of CO_2 sequestration technology systems showing the sources for which carbon compounds might be stored.

Courtesy of Cooperative Research Centre for Greenhouse Gas Technologies, CO2CRC.

might be taken. The Intergovernmental Panel on Climate Change has identified four basic systems for capturing CO_2 from use of fossil fuels and/or biomass processes:

1. Capture from industrial process streams
2. Postcombustion capture
3. Oxyfuel combustion capture
4. Precombustion capture.[6]

The probable critical paths of these technologies are shown in Figure 7.12. Thus, there are numerous ways of conserving and adding to natural sequestration processes that could significantly decrease the net greenhouse gas concentrations in the atmosphere.

THE GOOD, THE BAD, AND THE MISUNDERSTOOD

All life on Earth consists of molecules that contain carbon. Carbon is part of every essential process that sustains life, including photosynthesis, respiration, and biodegradation. It is absurd to label carbon "good" or "bad" since its utility and harm are clearly dependent on time and place.

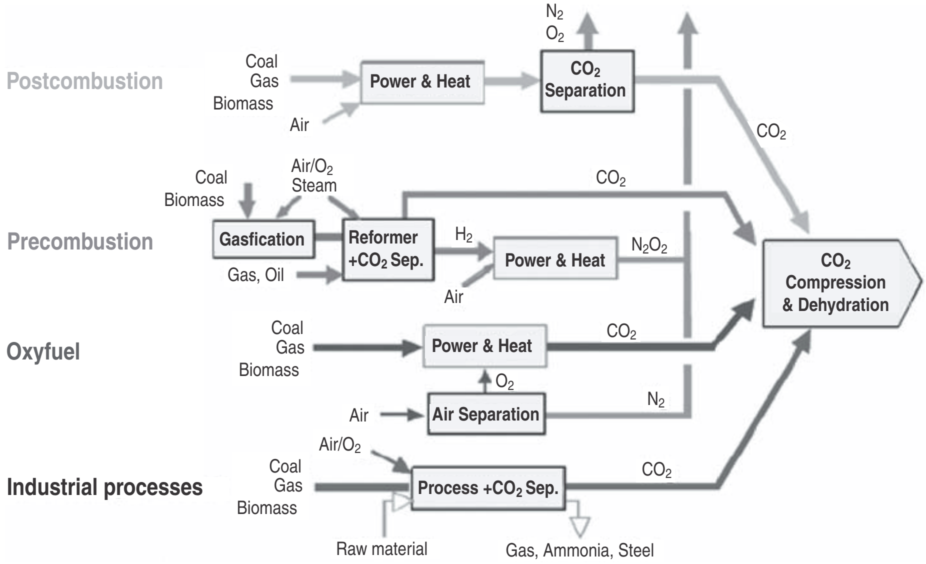


Figure 7.12 Potential locations of sinks available for carbon sequestration.

Courtesy of Cooperative Research Centre for Greenhouse Gas Technologies, CO2CRC.

Green engineering and sustainable design must consider the life cycle of carbon as it forms various chemical compounds. When oxidized it forms CO_2, and when reduced it forms CH_4. Both are important greenhouse gases. When in excess and when in the wrong place (i.e., the troposphere), both are problematic. Research and innovative thinking are needed on how best to limit releases to the atmosphere *and* to find ways to remove the excesses. Again, this requires a life-cycle perspective in design.

NOTES AND REFERENCES

1. For a complete explanation of the Henry's law constant, including how it is calculated and example problems, see Chapter 3.
2. The major source for this discussion is D. A. Vallero and P. A. Vesilind, *Socially Responsible Engineering: Justice in Risk Management*, Wiley, Hoboken, NJ, 2006.
3. A. C. Smith, W. P. Diamond, and J. A. Organiscak, "Bleederless ventilation systems as a spontaneous combustion control measure in U.S. coal mines", U.S. Department of the Interior, Bureau of Mines, Information Circular 9377, NTIS PB94-152816, Washington, DC, 1994.
4. M. A. Trevits, A. C. Smith, A. Ozment, J. B. Walsh, and M. R. Thibou. "Application of gas-enhanced foam at the Excel No. 3 mine fire," *Proceedings of the National Coal Show*, Pittsburgh, PA, June 7–9, 2005, Mining Media, Inc., Denver, CO, 2005.

5. C. Sabine, NOAA Pacific Marine Environmental Laboratory, Seattle, Washington, 2004, quoted in http://www.noaanews.noaa.gov/stories2004/s2261.htm, accessed August 26, 2007.
6. Intergovernmental Panel on Climate Change, United Nations. *IPCC Special Report on Carbon Dioxide Capture and Storage*, approved and accepted by IPCC Working Group III and the 24th Session of the IPCC in Montreal, Canada, September 26, 2005.

chapter 8

We Have Met the Future and It Is Green

Every generation needs a new Revolution.

Thomas Jefferson

In this book we have covered a wide range of topics, with the intention of exploring issues of process, scientific foundations, and ethical consideration often not addressed in the typical prescriptive design approaches offered in guidebooks, including those that advocate green design. We are suggesting the need to optimize among variables and within design constraints so that the collective effect of design is to improve the future. This is a step beyond sustainability. It is a transition from the "Me Generation" to "Regeneration." This view has been articulated by Richard Tarnas:

> It is perhaps not too much to say that, in the first decade of the new millennium, humanity has entered into a condition that is in some sense more globally united and interconnected, more sensitized to the experiences and suffering of others, in certain respects more spiritually awakened, more conscious of alternative future possibilities and ideals, more capable of collective healing and compassion, and, aided by technological advances in communication media, more able to think, feel, and respond together in a spiritually evolved manner to the world's swiftly changing realities than has ever before been possible.[1]

Another sage, Paul Hawken, author of *Natural Capitalism* and the recently published *Blessed Unrest*, sees a great deal to be optimistic about when taking into account the growing number of people actively engaging in what he believes to be the "largest social movement in all of human history," a worldwide movement that is beginning to have a positive impact in redefining human relationships with the environment and with each other. Hawken writes in *Blessed Unrest* that "if you look at the science that describes what is happening on earth today and aren't pessimistic, you don't have the correct data. If you meet the people in this unnamed movement and aren't optimistic, you haven't got a heart."[2]

This movement is composed of a diverse mix, a melting pot of farmer, writer, architect, teacher, engineer, and countless others. Among this diverse collection of emerging environmental stewards is a group with an intense passion for leading this ecological revolution, today's generation of youth entering college. Each year, we meet young people who make us optimistic. This generation is entering college today with a much greater awareness of the issues, hungry for knowledge, and eager to apply newly acquired knowledge in a way that makes a positive difference in both their communities and globally. Service learning opportunities provide students today with the ability to increase awareness of the social and equity issues of sustainability and to apply technical knowledge in a manner that provides students tangible feedback and results.

Sidebar: Engineers Without Borders–USA

Engineers Without Borders—USA (EWB–USA) is a nonprofit humanitarian organization born in 2000 in San Pablo, Belize, with the visit of a civil engineering professor, Bernard Amadei of the University of Colorado. Amadei visited this small village of 250 to explore the possibility of designing and implementing a solution for delivery of water to the village. Amadei returned to the village in May 2001 with eight students from the university, and for about $14,000 completed the project, not only providing water to the village but also improving the quality of life for the villagers and strengthening their community.* The EWB–USA "vision is of a world where all people have access to the knowledge and resources with which to meet their basic needs and promote sustainable development in such areas as water supply and sanitation, food production and processing, housing and construction, energy, transportation, and communication, income generation and employment creation." The by-product of investment in communities in need of this knowledge is the experience gained by emerging design professionals prepared to play a central leadership role in creating a more sustainable future.

*Engineers Without Borders–USA, http://www.ewb-usa.org/history.php, accessed August 22, 2007.

APPROPRIATE TECHNOLOGY AND THE HOME DEPOT SMART HOME AT DUKE UNIVERSITY

Figure SH8.1 Appropriate Technology: Photovoltaic panels that were sourced locally and installed using local labor in a rural Ugandan village.

An "Appropriate Technology" is a technology that is suitable for the geographical, cultural, or economic situation in which it is used. The term appropriate technology is often used to refer to technology deployed sustainably in the developing world. In the context of the developing world an appropriate technology is usually sourced locally, constructed of local materials, built using local labor, benefits the local economy, and improves quality of life in the local community.

DEVELOPING A RESOURCE CENTER IN RURAL UGANDA

Appropriate technology was deployed in rural Uganda as a partnership between the Duke University chapter of Engineers Without Borders (EWB), the Duke Smart Home Program, and The Rural Agency for Sustainable Development (RASD). RASD is a Ugandan non-governmental organization (NGO) based in Nkokonjeru dedicated to providing free or low-cost information about sustainable living to the local community. The project focused on enabling RASD to achieve their goals by finishing construction on the 1000 ft^2 main facility, providing a solar power station rated at 162 watts, providing a low power 40 watt computer cluster composed of 2 Linux computers, furnishing the cluster with a digital library of 1500 books focused on appropriate technology, and providing a Universal Nut Sheller made by the Full Belly Project for increasing the value of locally harvested coffee. All systems were implemented at 100% functionality and all supplies were either commodities, or were sourced locally. Local labor was utilized for the implementation effort, and relationships were formed with local solar providers and local computer providers for both short and long-term maintenance needs.

As we consider what it will take to move toward the regenerative view, here are a few predictions, along with some attendant questions.

PREDICTIONS FOR THE FUTURE

Science

The future will see acceleration in the trend of scientists, engineers, and architects looking to nature for understanding and inspiration for design solutions. The concept of biomimicry is really only in its infancy, with much yet to be revealed. Nanotechnology will offer many solutions to some current problems but will also offer new challenges as we deal with questions never before considered. For example, how does the concept of design for disassembly and the notion "waste equals food" work at the nanoscale?

The Professions

The architecture and engineering community must evolve from the current thinking of sustainability and the primary focus on efficiency and high performance to the concept of regenerative design. One such example is Architecture 2030, a nonprofit, nonpartisan, and independent organization with the mission of transforming the building sector from the current position of being the major contributor to greenhouse gas emissions to playing a key role in solving the global warming crisis. The target put forth in the Architecture 2030 Challenge is that by 2030, buildings will be carbon-neutral, using no fossil-fuel greenhouse gas–emitting energy to operate.

The Government

Federal, state, and local governments are beginning to respond to the growing environmental crisis by drafting and implementing new standards for building performance. This trend will continue, with California's Title 24 Efficiency Standards providing a successful model established in 1978 to reduce the state's energy consumption. The standard is updated periodically to incorporate new innovative technologies and methods, with the 2005 version currently being upgraded, and a new standard slated for in 2008. In addition to jurisdictions exercising regulatory powers, incentives are another form of future governmental action, which will continue to evolve as a stimulant for change. Financial incentives in the form of tax relief, rebates, grants, and loans are already in existence in several states and local municipalities. There are also entities implementing nonfinancial incentives to recognize sustainable design by providing expedited plan review and approval. In the state of Washington, the King County Department of Development and Environmental Services has developed a program entitled "Green Track." For green buildings and low-impact development projects, the county offers a customized review schedule with an assigned project manager, free technical consulting, cost sharing, and fee discounts for implementing best management practices and a host of other services intended to encourage sustainable development and green building practices.

The federal government may also have a future role to play in establishing a common yardstick for measuring environmentally acceptable products. The building of a national database of materials would provide a role similar to that played currently by the Food and Drug Administration in the nutrition labeling now found on food packaging and prescription drugs. This database would provide informational content independent of a manufacturer's product, data that would provide architects and engineers with the "ecological nutritional content" of materials, including information on embodied energy, toxins included in both the finished product and its manufacturing, and comparison to alternative materials to provide an "average daily content" or "potential side effects" type of benchmarking. For example, manufactured products that include polyvinylchloride may be thought to be benign once in place, but labeling would include information on the hazards associated with exposure during manufacturing and the hazards if exposed to fire.

In fact, this all could be digitized and made readily available as a type of "life cycle on a chip." As a new product is released, designers, builders and other users could access information, which could be updated continuously by visits to an internet website.

Education

Curriculum is emerging in schools of engineering and architecture to introduce students to the principles of sustainable design and engineering. The authors' experience has been that there is not only a gap in the traditional core curriculum that needs to be filled, but that today's college students are looking for opportunities to expand their awareness of the issues that will confront future generations and build knowledge that will provide a foundation for conceiving solutions to the most pressing problems.

At Duke, for example, students have taken their own initiative to enter into design experiences at home and abroad. In recent years, they have engaged in team projects in Indonesia and Africa, all with green engineering emphases. We will address some of the lessons we have learned from teaching this course at the conclusion of this chapter.

Energy

Peering through the lens to the future of energy generation presents a paradoxical picture. On the one hand, the picture is clear in that a transition must occur from the current status of a carbon-based economy dependent on fossil fuels as the primary source of energy production. In many ways, the picture also remains unclear as to the composition of alternatives that will replace current sources. Will we transition from a carbon economy to a hydrogen economy? Will nuclear energy re-emerge as a "green energy" source? After all, it releases virtually no carbon compounds. However, issues like long-term storage of highly toxic wastes continue to vex the nuclear power industry. Wind, photovoltaics, biofuels, hydrogen, tidal turbines, and still emerging innovations all provide potential answers as well as new questions. What we do know is that the laws of thermodynamics will play a central role in determining which are most successful.

Economics

Economics will certainly play a central role in the future of sustainable design and engineering, but change is already occurring in the actual metrics of how performance will be measured. An example of this change can be witnessed in the changing attitudes of the development community toward sustainable design. Once viewed with skepticism and a threat to the bottom line, the economic advantages are coming into focus as life-cycle assessment tools begin to tell a more complete story of performance. In addition to the measures of energy consumption, a growing body of research is now pointing to the benefits to the corporate bottom line by way of productivity gains. The linking of employee productivity and well-being to the built environment is changing the traditional measures of cost–benefit analysis. The impact of a subtle change in productivity considered over a modest time frame can make the case for looking beyond the "first cost" entry of the bottom line.

FROM SUSTAINABLE TO REGENERATIVE DESIGN

Perhaps the greatest lesson being drawn from reexamination of the natural environment is the notion of continuous, regenerative processes or cycles found in nature. The shift in focus is from a mind-set of finding ways to be more efficient with material resources and working to minimize the impact on the environment, to adopting a "whole systems" and "integrated" approach to design that seeks symbiotic solutions. In *Cradle to Cradle*, McDonough and Braungart write of nature's cycles of nutrient flow and metabolism in which "waste equals food."[3] The nutrient building blocks of carbon, hydrogen, oxygen, and nitrogen reside in continuous cycles in what is, with rare exceptions, a closed planetary system. The authors propose a new way of looking at materials by classifying them as either biological or technical nutrients. "A biological nutrient is a material or product that is designed to return to the biological cycle—it is literally consumed by microorganisms in the soil and by other animals." In contrast, "technical nutrients are designed to go back into a technical cycle, into the industrial metabolism from which it came." Rather than being "down-cycled" to a less productive use or discarded as waste in a landfill, these technical nutrients reenter the system as productive inputs to a new cycle.

This new paradigm of whole systems thinking requires the design community to become better versed in understanding the environmental systems of the places in which they live. An understanding and appreciation for the biology and chemistry of living systems and the geology, hydrology, and meteorology of place must complement the traditional technical knowledge of concrete, steel, and other materials and methods. Future architects and engineers must not only be equipped to understand the technical nutrients and embrace new ideas, such as design for disassembly, but must also become familiar with biological nutrient cycles. Being versed in both scientific and engineering principles becomes a prerequisite in the search for symbiotic design solutions.

Mass Production to Mass Customization

The Nike company now has the ability to produce athletic shoes, apparel, and equipment to meet customers' exact specifications, not only as to the size of a shoe but also as to sport, material, color, personal styling of the laces, lining, and a personal message, thus providing for thousands of possible variations. The NIKEiD tag line is: "Choose your colors. Add your personal motto. Make it your own." This evolution in the manufacture of consumer goods from a mind-set of economies of scale gained from mass production and limiting choice to a mind-set of leveraging technology to meet detailed individual specifications offers possibilities that can be transferred to creation of the built environment.

In *Refabricating Architecture*, authors Stephen Kieran and James Timberlake note that "we can return to master building. We can reestablish craft in architecture by integrating the intelligence of the architect, contractor, materials scientist, and product engineer into a collective web of information."[4] Although our primary focus is on the manufacture and delivery process, this integrating of intelligence and collective web of information provides for mass customization that is able to take into account many facets of the design process that will lead to more sustainable design solutions, from response to the uniqueness of each site's climate to the life-cycle implications of material selection. This requires a fundamental reexamination of the traditional processes of design and construction which segregates intelligence and information in a purely linear process and has remained relatively unchanged for centuries.

Sidebar: Applying the Synthovation/Regenerative Model: Intelligent Design

The trend in integrated and systematic design is being embraced vigorously by architects and engineers. The green model is applied to products, devices, buildings, and other systems. Adding sustainability to the stepwise process through systems such as ISO 14001, pollution prevention, design for the environment, and LEED has been a dramatic paradigm shift in design process. The professions seem poised for the next step, beyond sustainability.

The regenerative viewpoint takes the next step toward the goal of designing and shaping our environment in a way that seeks symbiotic relationships between humans and the other organisms sharing the planet. If the design community is to take the next step toward this goal, the mental model must continue to evolve from one of minimizing harm to one of building an awareness and knowledge of the science of place and the living systems that will allow architects and engineers to do what they do best. That is, from a project's conception they must synthesize innovative solutions that grow from engaging a diverse cross section of expertise in a collaborative process. Pamela Mang makes a compelling argument for the need for regenerative design work in an article published in *Design Intelligence*. Paraphrasing Mang, regenerative design:

1. Takes place in a collaborative interdisciplinary process
2. Is built upon complex dynamics of multiple interacting systems and the ability to see the underlying patterns that are structuring them
3. Draws upon courage and creativity—using what has worked but creating it anew to fit a specific place

4. Is grounded in the faith that the world is not random but purposeful, and in the belief that as part of a larger order, humans must act in harmony with those larger patterns.*

Regenerative design is the next step beyond sustainable design. Why sustain something for the next generation that is very good when we can set the stage for them to build something even better?

*Pamela Mang, "Regenerative design: sustainable design's coming revolution," *Design Intelligence*, July 1, 2001.

Building information modeling (BIM) is an emerging tool that has been introduced into the classroom to facilitate students' understanding of the relationship between design decisions and building performance. BIM uses computer technology to create a virtual model of the design and is intended not only as a tool for documentation but also to provide a tool for testing alternative scenarios and measuring each scenario across multiple benchmarks, from material use to energy consumption. The tool transforms the traditional process of the computer simply as a tool to document, to one of conducting analysis of all of a building's systems in an integrated fashion. The potential for these models to behave in a much more "intelligent" manner provides a design team with the ability to test "what if" scenarios during the design process. With the development of more robust databases on the characteristics and composition of materials, for example, models will be able to reflect more accurately the life-cycle implications of a designer's decisions as the model incorporates, for example, the "embodied energy" of alternative materials from the point of extraction through manufacturing, delivery, and finished installation. These information-rich models are also able to simulate and analyze alternative scenarios that incorporate project specifics such as local climate, which are fundamental to sound and sustainable design strategies.

Perhaps the best way to approach the future of green design is to focus on those who will be the next generation of designers. So let us end the book by extracting the viewpoints of first-year engineering students engaged in green design. First, let us give a brief structure of such a course.

LESSONS FROM THE FIRST-YEARS

In teaching two courses, one aimed at undergraduates just entering Duke University and one aimed at engineering majors in the junior or senior year, we have learned much about green design. In this section, we share lessons on how to provide a simple framework to introduce students to the science and practical concepts of green engineering and design. The framework then builds on this foundation of awareness and enhanced knowledge by encouraging the students to be innovative in seeking integrated and systematically focused solutions.

The introductory course in green engineering and sustainable design at Duke University consists of five project teams, each assigned to one of the following topics in sustainability which parallel the LEED program outlined earlier:

1. Sustainable sites
2. Water efficiency
3. Energy and atmosphere
4. Materials and resources
5. Indoor environmental policy

Over the course of the semester, each student conducts in-depth research on a particular topic by completing three projects with teammates assigned to the same topic.

Studio I: Survey of the Literature

Objective: Students are asked to become the class experts in their specific topic by surveying related sustainability literature.

Requirements: Teams must survey a minimum of 15 articles or journal publications (five per member) that relate to their topic. These articles should cover the major issues in each topic, as well as proposed solutions and benefits from these solutions, and recent innovations in sustainability.

Deliverables: Required from students are a list of each group's sources, with a brief synopses explaining the relevance to the topic, and a 10- to 15-minute class presentation to their classmates, providing an overview of their findings.

Studio II: Application of Sustainability Principles and Concepts

Objectives: As a group, students analyze a selected building on campus for elements related to their topic. Each group presents its findings to the class to create a comprehensive and concrete picture of sustainability issues for a single system.

Requirements: Using information from the students' literature surveys, the students are asked to examine the building and to identify at least three examples of sustainability issues related to their topic. For each example they identify (1) the problem or design shortcoming, (2) the way it is currently addressed in the existing structure, (3) any improvements or changes that the group would make to this solution, and, (4) the benefits of their suggested improvement for the system. Students are encouraged to visit the site to make observations and to interview users of the building to gain from their perspective.

Deliverables: A 10- to 15-minute class presentation explaining findings and recommendations.

Studio III: Innovation

Objectives: Students are required to use their in-depth understanding of one topic in sustainability, combined with their broad understanding of general issues in sustainability as they relate to a single building, to create an innovative and sustainable development.

Requirements: This development can be a redesign or design improvement, a retrofit, or an entirely new device. Students ultimately complete this portion of the project individually, but are encouraged to collaborate with their classmates in the process of developing their innovation. If their design is exceedingly complex, they may be allowed to work in teams. They must demonstrate a clear grasp of the problem that their innovation addresses, and identify and quantify or characterize the improvements made with their innovation. Students are also required to justify why it would be beneficial to use this device or design compared to current standards.

Deliverables: A 5- to 7-minute individual presentation and visual aids showing the development of the innovation using model prototypes, drawings, or other communication tools necessary to describe the innovation.

The interactive/discovery pedagogical style has proven effective in achieving the three objectives of building awareness of issues, understanding principles, and applying knowledge. An exercise that has proven to be successful at facilitating this process of discovery for students is built around the U.S. Green Building Council's LEED program. Students are given a three-part assignment that is initiated by the instructor with an overview of five primary categories: sustainable sites, water, energy and atmosphere, materials and resources, and indoor environment. Studio I of the assignment requires that students form groups and conduct research on one of the five topics and provide classmates with an overview that addresses the benefits of current design and engineering strategies as well as an introduction to emerging innovations. In addition to the research, students are required to examine the scientific underpinnings of their subject. For example, the sustainable sites group would not only address techniques for reducing stormwater runoff but also seek to understand the science of soils or the impact on habitat of suspended solids in receiving streams. The student group's presentations provide the opportunity for interaction, with the instructors and classmates providing fertile discussion and debate. Although this discourse is facilitated initially by the instructor, students learn a great deal from the insight of other groups and begin to discover common principles that apply across subject boundaries.

At the outset, the instructors give targeted lectures and homework on thermodynamics, motion, and principles of chemistry and biology.

Studio II of the exercise is structured to build on the foundation of awareness of the subject matter in Studio I by providing students with an opportunity to understand how these strategies may be applied to an existing structure to improve performance. The use of an existing structure provides a tangible subject for students to observe and examine in detail. The exercise requires students to look for ways to optimize performance beyond the current state and to consider not only the potential benefits but also the collateral impact of their decisions on other facets of the structure. One tool in this effort is the life cycle analysis.

Studio III of the exercise requires students to build on their growing knowledge of the specific subject matter and the knowledge gained from their classmates, and to apply this knowledge by conceiving an innovative approach to a sustainable design challenge. Although, as mentioned, this is usually redesign or design improvement to an existing system, a retrofit, or an entirely new device, in some cases the innovations proposed by students are not physical objects but strategies for public policy or educational initiatives. These innovations build public awareness, entrepreneurial business models that address the "triple bottom line," or strategies that in some other way advance the goal of creating more sustainable environments.

Science and technology will play a pivotal role in addressing the sustainability challenges nationally and globally in the twenty-first century. The next generation of architects, engineers, and designers will be the primary source of ingenuity for developing innovative technologies in the lab and finding applications to real-world problems. The primary goal of challenging students with this exercise is to be innovative in their thinking and examine their world in a way that they may not have otherwise. Although many of the solutions may almost certainly have flaws yet to be resolved, the exercise will have achieved the objective and provided the class with a forum for critiquing the innovation solutions and for sharing perspectives that make for robust and fertile discussion in the classroom.

LOW-TECH DESIGN BASED ON OUTSIDE-THE-BOX THINKING

The student's innovation proposals can generally be organized in three categories. The first group includes low-tech solutions to sustainable challenges derived from "thinking outside of the box" or reexamination of a system they have observed

Figure 8.1 Exercise bicycle with magnetoalternator to generate electrical energy during workouts at Duke University.

many times before but have taken another look at through an alternative lens that illuminates new possibilities. An example of this approach is the case study of senior civil engineering student, Jim. Jim chose to look at the standard exercise bicycles in the student recreation center on campus and to view the bikes as a source of energy generation rather than simply as vehicles for providing the resistance necessary to build stamina, lung capacity, and muscle tone (see Fig. 8.1).

By studying several precedents, including custom bikes and laptop computers, and seeking to understand the functional and operational characteristics of generators and alternators, Jim was able to begin to devise a solution that he could test to determine the amount of energy production that would be possible for each bike. Also taken into consideration in his model was the density of the exercise bikes in the recreation center, along with other pieces of equipment (e.g., treadmills, ellipticals, stairsteppers), which also represented the potential for human-generated energy: 80 systems in all. Assumptions on actual time of active use, operating hours for the center, and the average estimate of 0.3 hp/hr for each device yielding 750 W/hp resulted in 472.5 kW/week. The amount of energy produced during a workout depends on biomechanical power generated. This, of course, varies substantially within a population. Even a relatively narrow stratum such as healthy college-age persons who use workout facilities includes much diversity in amount of conversion of mechanical to electrical energy (see Fig. 8.2).

Based on the local utility cost of $0.06/kWh, the net savings annually was about $1500. Although modest in the overall cost savings annually as a percentage of the total cost, other benefits were identified that were less tangible. These noneconomic benefits included a social return on investment as students are able to see the positive impact of their efforts displayed on each machine's LED (lightemittingdiode). In addition, there are environmental benefits of setting a positive example in generating green power.

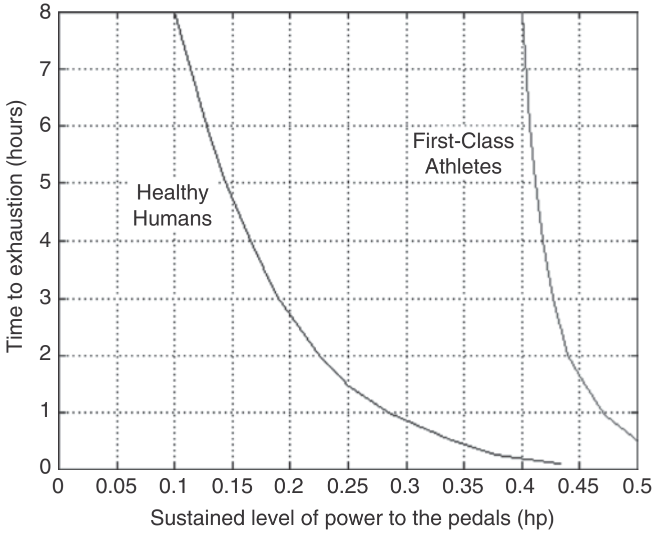


Figure 8.2 Power generation of cycling for a general population of healthy adults and competitive athletes compared to extinction (fatigue).

In a similar search for a more environmentally friendly source of fuel for a college campus, junior electrical engineering major Kamaal's innovation proposal sought to replace the traditional source of coal for firing the central steam plant on campus. Kamaal's "Green Steam" innovation resulted from an examination of the current coal-fired boilers and a study of the upgrades to the system since its original installation, aimed at improving performance efficiency. In her study of the environmental impacts of the current system, Kamaal identified several concerns, including:

- Particulate matter from incomplete combustion in the form of bottom ash and fly ash
- Sulfur dioxide emitted in a gaseous form, which contributes to respiratory illness, visibility impairment, acid rain, and the potential for altering the pH of soil and water
- Nitric oxide emitted, which contributes to global warming as a greenhouse gas and is also a respiratory irritant
- Carbon monoxide emissions, which depending on the fuel oxidation efficiency of the coal and the combustion process, can in high concentrations cause human sickness and is also a greenhouse gas
- Other volatile or semivolatile organic compounds formed as products of incomplete combustion

Kamaal suggested switchgrass (*Panicum virgatum*) as a biofuel to replace coal. Switchgrass, a perennial warm-season grass with coarse stems, has a heating value of 18.3 GJ/ton, with lower percentages of ash and sulfur than those in coal. Although her analysis suggested that switchgrass contains only about half of the heating capacity of coal, other economic analyses could prove this comparison to be incomplete. In fact, switchgrass compares favorably to other biofuel feedstocks (see Table 8.1). A study of recent facility management reports noted that the price

Table 8.1 Comparison of Physicochemical Properties of Switchgrass (*Panicum virgatum*) as a Biofuel Feedstock Relative to Selected Alternative Fuels[a]

	Switchgrass	Alternative Fuel	
Fuel Property	Value	Value	Fuel Type
Energy content (dry) (MBtu Mg^{-1})	17.4	18.6	Wood
		26.0	Coal
Moisture content (harvest) (%)	15	45	Poplar
Energy density (harvest) (MBtu Mg^{-1})	14.8	10.2	Poplar
Net energy recovery (MBtu Mg^{-1})	17.0	16.4	Poplar
Storage density [kg m^{-3} (dry weight)]		150	Poplar chips
(6 × 5 ft) round bale	133		
(4 × 5) ft round bale	105		
Hopped	108		
Hollocellulose (%)	54–67	49–66	Poplar
Ethanol recovery (L kg^{-1})	280	205	Poplar
Combustion ash (%)	4.5–5.8	1.6	Poplar
Ash fusion temperature (°C)	1016	1350	Poplar
		1287	Coal
Sulfur content (%)	0.12	0.03	Wood
		1.8	Coal

Source: S. B. McLaughlin, R. Samson, D. Bransby, and A. Wiselogel "Evaluating physical, chemical, and energetic properties of perennial grasses as biofuels," *Proceedings of the 7th National Bioenergy Conference: Partnerships to Develop and Apply Biomass Technologies*, Nashville, TN, September 15–20, 1996.

[a] Energy content of switchgrass was determined from six samples from Iowa. Bale density and chopped density of switchgrass are from Alabama (Bransby, Auburn). Poplar chip density is from studies of White et al. (M. S. White, M. C. Vodak, and D. C. Cupp, "Effect of surface compaction on the moisture content of piled green hardwood chips," *Forest Products Journal*, 34, 59–60, 1984). Poplar energy moisture content, combustion ash, and ash fusion temperatures are from NREL, as are the ash fusion temperatures and sulfur contents of all fuels. Energy density is the energy per unit of wet harvest weight. Net energy recovery considers energy lost in drying fuel prior to combustion. The holocellulose content of switchgrass is from seven varieties in Alabama S. E. Sladden and D. I. Bransby, "Improved conversion of herbaceous biomass to biofuels: potential for modification of key plant characteristics," Technical Report ORNL/Sub/88-SC011/1, Oak Ridge National Laboratory, Oak Ridge, TN, 1989) and from seven hybrid poplar varieties in Pennsylvania T. W. Bowersox, P. R. Blankenhorn, and W. K. Murphey, "Heat of combustion, ash content, nutrient content, and chemical content of *Populus* hybrids," *Wood Science*, 11, 257–262, 1979). Ethanol yields are averages of simultaneous saccharification and fermentation recovery on three analyses per species using a standard recovery procedure for all feedstocks. Ethanol yields can probably be improved somewhat by tailoring reaction mixtures to each specific feedstock; thus, those should be considered preliminary measures of potential recovery.

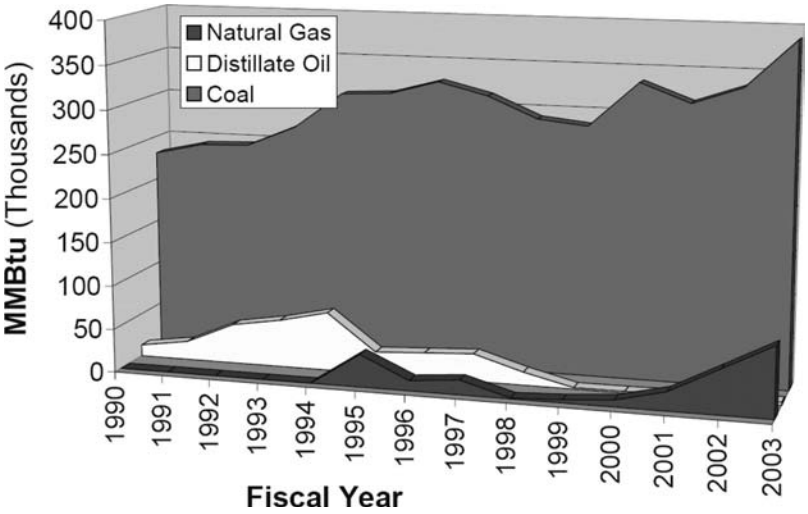


Figure 8.3 Annual fuel consumption at Duke University's steam plant from 1990 to 2003.

From S. Hummel, "Charting a path to greenhouse gas reductions," *Greening of the Campus VI Proceedings*, Ball State University, Muncie, Indiana, September 15–17, 2005.

of coal had risen "37% and availability to the campus remains very tight,"[5] so it would benefit users to have alternative fuel sources. In fact, universities are very good candidates for conversion from coal. Energy requirements at Duke University are met predominantly by coal (see Fig. 8.3). As evidence, the superintendent of the steam plant services group of Duke University, Dennis Kennedy, noted that the coal shortage had affected the plant several times over the past winter and depleted their stores to less that a 10-day supply (see Fig. 8.4). This also led to the need to augment supplies with other nonrenewable fossil fuels (see Fig. 8.5).

Switchgrass is a locally available crop traditionally found in the southeastern United States with an average farm gate price in North Carolina of $38.30/ton, compared to an average of above $50/ton, with significant seasonal variation, for coal, according to data from the Energy information Administration Office. North Carolina State University has received government grants to study crops, including swithgrass for power generation. Kamaal's proposal included an alternative that would burn swithgrass in existing stacks and consider a blend of coal and switchgrass, depending on the time of year, prices of the two commodities, and the system's demands for performance. The transition to switchgrass as a feasible alternative fuel source for generating steam is being made more attractive by the university's recent transition to biodiesel fuels for campus buses and its commitment to sustainable practices.

The third innovation project in this group was conceived by senior civil engineering major, Tom, who recommended harnessing the potential energy of moving water in plumbing systems in high-rise construction. Tom's initial research focused on understanding the components of typical water systems used in high-rise construction. This included hot water, domestic water, chilled water, and the pumps used to boost water pressure. His research included examining

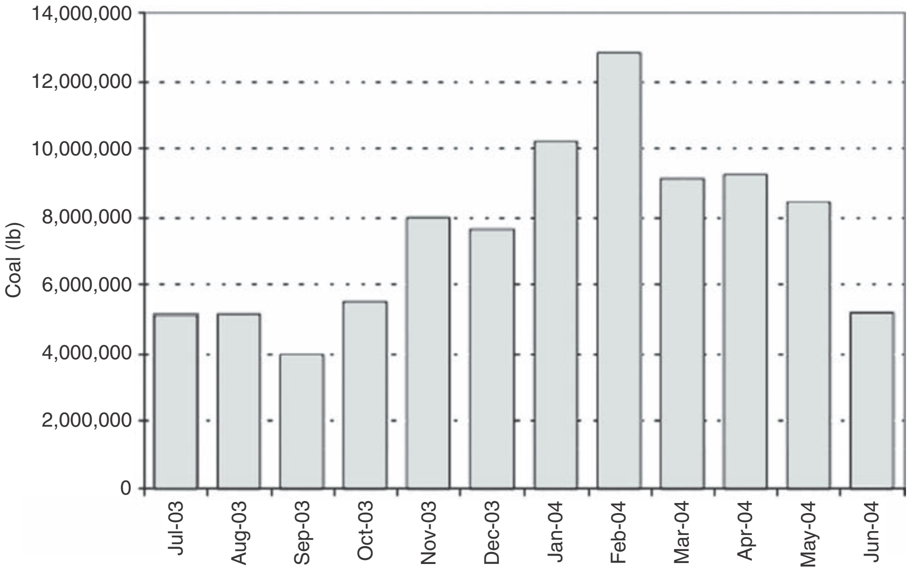


Figure 8.4 Monthly coal combustion at Duke University from July 2003 to June 2004. Note that the seasonal variability profile differs from that of general electricity-generating facilities, with the largest consumption taking place in the summer months. However, at universities, the demand is higher during the school year.

firsthand analogous systems in the engineering building on campus as he sought to gain an understanding of how the systems operate. Several high-tech alternatives were considered that involved using elevated storage tanks to create static head to pressurize the system. Working with accumulators and hydropneumatic tanks, a relatively low-tech solution emerged, *gray water generation*. In this process, a small hydroelectric turbine tied to the water-return piping system converts the motion of water into electrical energy, converting potential energy to kinetic energy (see Fig. 8.6).

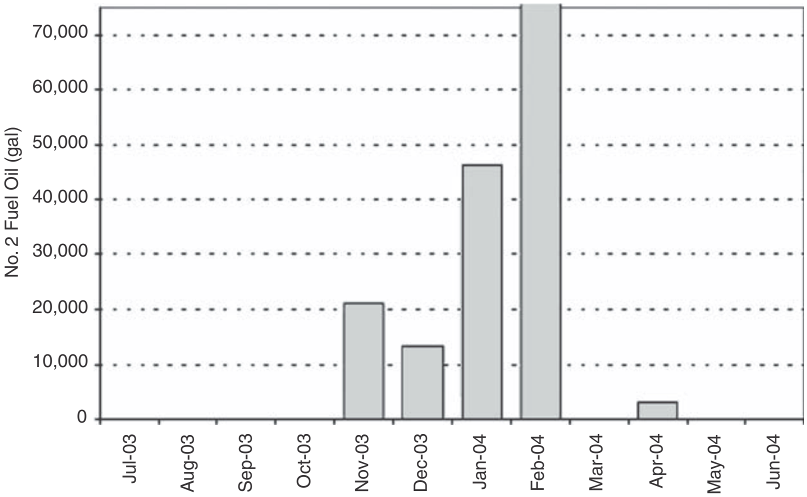


Figure 8.5 Augmentation of coal with fuel oil at Duke University from July 2003 through June 2004.

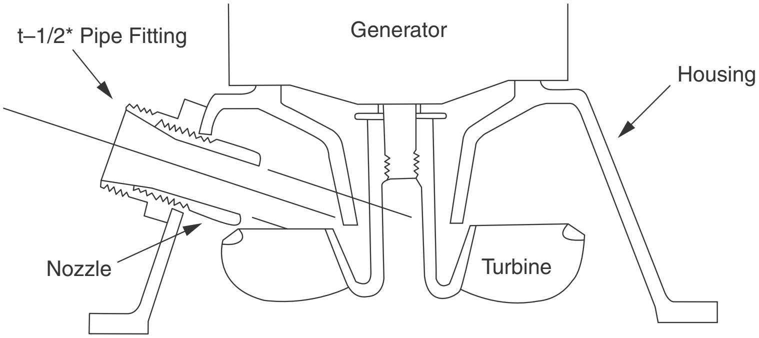


Figure 8.6 System that combines a hydroelectric turbine with a water-return piping system to convert the mechanical energy of moving water into electrical energy.

From NoOutage.com, http://www.nooutage.com/images/esd-turgo-cutaway.gif.

Sidebar: Water Consumption

The Internet is a good source for calculating water demand. For example, the Computer Support Group, Inc. (CSG) and the CSGNetwork.com Web site has a "water consumption calculator," http://www.csgnetwork.com/waterusagecalc.html. This provides information on locations and types of water use. The first step in conservation is an inventory of present use. From there, adjustments to design can be made to arrive at a plan that reduces the demand for water. The calculator provides an estimate of household consumption both indoor and outdoors. After calculating water-use patterns, the designer can build in ways to conserve based on the clientele's lifestyle.

The water is contained in a tall vertical pipe until a set static head pressure is achieved. Automated control systems would be used to determine when sufficient pressure is present and return the energy generated to the power grid or to battery storage used for operating booster pumps. Using rainfall data and roof-area calculations, Tom calculated the static head and from this the hydroelectric potential power output. Since power increases logarithmically with static head, the taller the building, the more power that is potentially produced (see Fig. 8.7). The approach would require the addition of a central, vertical gray water collector pipe along with some additional electrical and controls wiring to operate the system, and roof structure designed to collect rainwater for use in the system. Vallero contacted the manufacturer of the turbine to discuss possible design challenges. The manufacturer's representative mentioned that gray water can be much more corrosive than unpolluted water, so the turbine parts may need to be modified to include more chemically resistant materials. The resulting power generated is again modest, but the innovation provides a springboard for further exploration of the use of gravity and potential energy created by static pressure head in building systems to generate power locally.

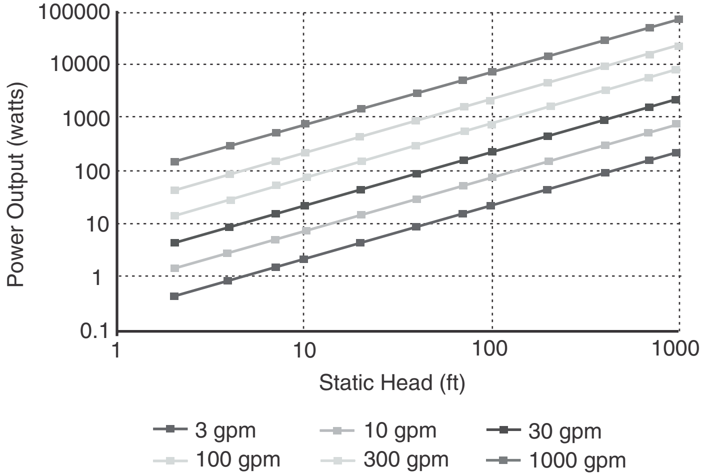


Figure 8.7 Comparison of static head and log power output. Power output increases logarithmically with head.

From NoOutage.com, http://www.nooutage.com/images/hydroelectric-potential.gif.

NOTES:

1. Graph assumes 50% system efficiency and 20%, head loss in pipe due to friction. Efficiency may be better at high heads. Friction losses will less with larger diameter pipe.
2. Example reading of graph. For a 10 ft head with a flow of 300 gpm the estimated output would be 200 watts.
3. Graph based on following formula: head × (1-loss) × flow × 0.10 × eff - watts Using example values: 10 ft × (1-0.20) × 300 gpm × 0.10 × 0.50 – 216 watts.
4. For additional information see our web site at http://www.NoOutage.com or send e-mail to info@NoOutage.com

INTEGRATED LIFE-CYCLE THINKING

Several student projects arrived at innovative solutions by embracing the concept of life-cycle thinking and concepts of integration of systems to achieve a "whole" system greater than the sum of the individual components. Senior mechanical engineering major Hunter attempted to create a "smarter," integrated system of water use in buildings, from potable water to water as a heating and energy source. The goal of Hunter's project was to integrate these systems in a manner that would make them economically practical where current system components had not yet become feasible as independent systems. Hunter's motivation grew from his experience on the Home Depot Smart Home at Duke University (www.smarthome.duke.edu/) and the challenges of incorporating photovoltaic (PV) technology (see Fig. 8.8) in a way that made it economical in a cost–benefit analysis. The PHD (power, heating, and drinking) system sought a solution that utilizes both the products and by-products of solar power production to power, heat, and provide potable water for the home. Hunter's research suggested that there could be a way to take the waste heat from the photovoltaic cells and use this as a heating source (see Fig. 8.9). His findings indicated that at temperatures

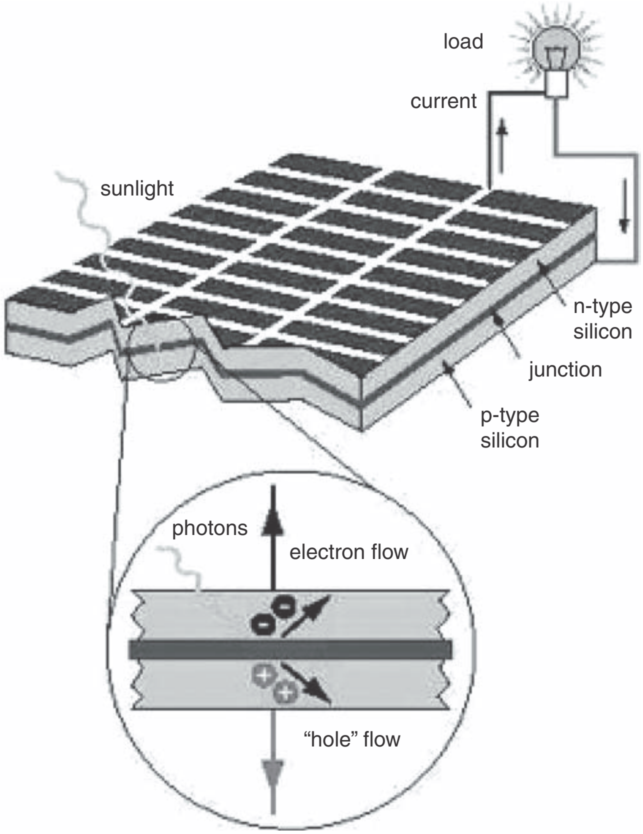


Figure 8.8 Photovoltaic system employed at the Home Depot Smart Home at Duke University. The system converts radiant energy from the sun to electricity. Radiant energy passes through a glass cover with a nonreflective coating onto a silicon (Si) “sandwich.” The Si atoms are arranged in a cubic matrix. The n-layer has excess electrons that will exit, whereas the p-layer is missing electrons (i.e., it has electron holes). Thus, each PV cell is configured like a battery, with a positive and a negative side, separated by a permanent electrical field (the junction). The electrons flow from p to n exclusively. A photon that hits the n-layer releases an electron that remains in the n-layer. Conversely, a photon that hits the p-layer also releases an electron, but it moves easily to the n-layer. The excess electrons that accumulate in the n-layer are allowed to exit via a conducting wire. Thus, a direct current is generated as electrons flow from the negative side to the positive side, as long as there is sunlight to produce radiant energy and its photons, there will be excess electrons flowing (i.e., there will be a continuous electrical current). The current is delivered to a *load* (depicted here as a light bulb). The system can be even more efficient if excess electrons not used by the load are stored in a battery. Thus, PV systems are improving commensurately with advances in materials (e.g., glass, coatings, sandwiches) and batteries.

up to 150°F, voltage output in the panels can drop as much as 20%, and that in a typical solar panel, only 14% of the sunlight is converted to electricity, 7% is reflected, and 79% is converted to heat.

Because of the heat gain, PV panels are mounted above the roof surface to provide air circulation below the panel. The proposal laminates PVs to a corrugated panel through which water may flow, simultaneously cooling the panels and heating the water. The heated water is stored in a *hot tank* for use in a dishwasher, for washing clothes, and so on. The laminating of the PVs to the corrugated surface also makes it possible for the surface to move and “track” the path of the sun to maximize the collection period each day. Hunter’s innovation proposal suggests that the potential to capture this waste heat could eliminate or at least offset some of the household energy used to heat water, this energy use on average typically being 30% of the total household energy consumption.

Harvesting rainwater from the surface of the panels provides a portion of the water used to cool the panels and feeds a second storage tank, the *cool tank*. The final aspect of the proposal is the use of rainwater that has been harvested

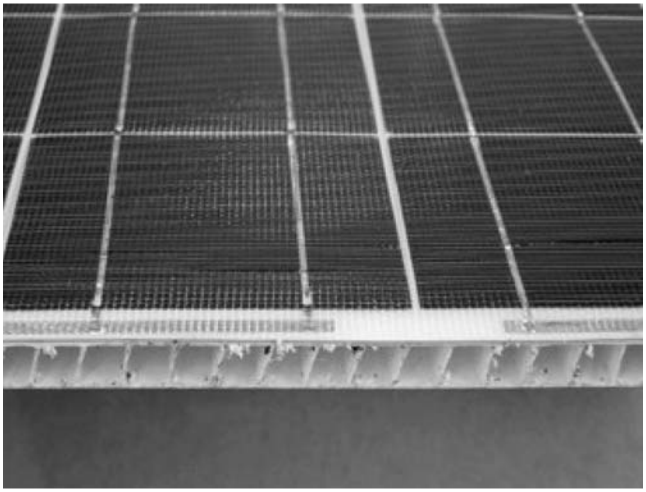


Figure 8.9 Photovoltaic system in use at the Home Depot Smart Home at Duke University, showing reflective glass and silicon sandwiches. The hollow areas could be used to transport heated air.

and stored in the *cool tank* as a source for radiant floor heating in the home by circulating it through the panels to heat the water and begin to circulate it through the house floors. When excess capacity exists or heating is not required in the home, the water may be diverted for nonpotable uses. In addition to capturing the waste heat and using this to heat water and the interior of the home, water is captured in a closed loop and cycled through the system, resulting in significant savings in potable water use. Using the average statistics for water use in a four-person household, Hunter arrived at a savings of 114 gallons a day, 3466 gallons a month, and 41,610 gallons a year.

Rethinking the life cycle of the typical toilet paper roll led Saul, a graduate student in engineering management, to consider how a product used by millions everyday might be made more friendly to the environment. Saul began his search for innovation by collecting data that provided insight into the scale of use of cardboard rolls. The Charmin Company has gathered data which indicate that the average American uses 57 sheets of toilet paper a day, translating to 20,805 sheets a year. With the average roll containing 400 sheets, the average person will use four rolls a month, discarding four cardboard rolls each month based on a nonscientific survey which suggested that few, if any, Americans actually recycle the rolls. Taking the current U.S. population and making an allowance for primary users between the ages of 5 and 86, the four average rolls per month yields a staggering annual consumption of 1,174,676,430 rolls.

The manufacturing process for paper tubes is very simple. Recycled paper is pulled out from a paper roll cassette, put in a jar filled with glue, rolled again in a spiral by a winder, and cut into pieces of a designated length. Saul's goal was to devise an alternative which would be composed of natural materials of nonwood and nonsynthetic chemical content and to create a substitute that would have a low impact on the environment during extraction, manufacturing, and disposal, be totally compostable, and be returned to the earth at the end of the life cycle. A review of nonwood natural fibers led to research on polylactic acid (PLA).

PLA is made of glucose from agricultural crops such as corn and potatoes and is fully biodegradable and amenable to composting. The process to produce PLA breaks down the plant starches into natural sugars. Carbon and other elements are used to make polylactide in a simple fermentation and separation process. Advantages of PLA noted in Saul's research:

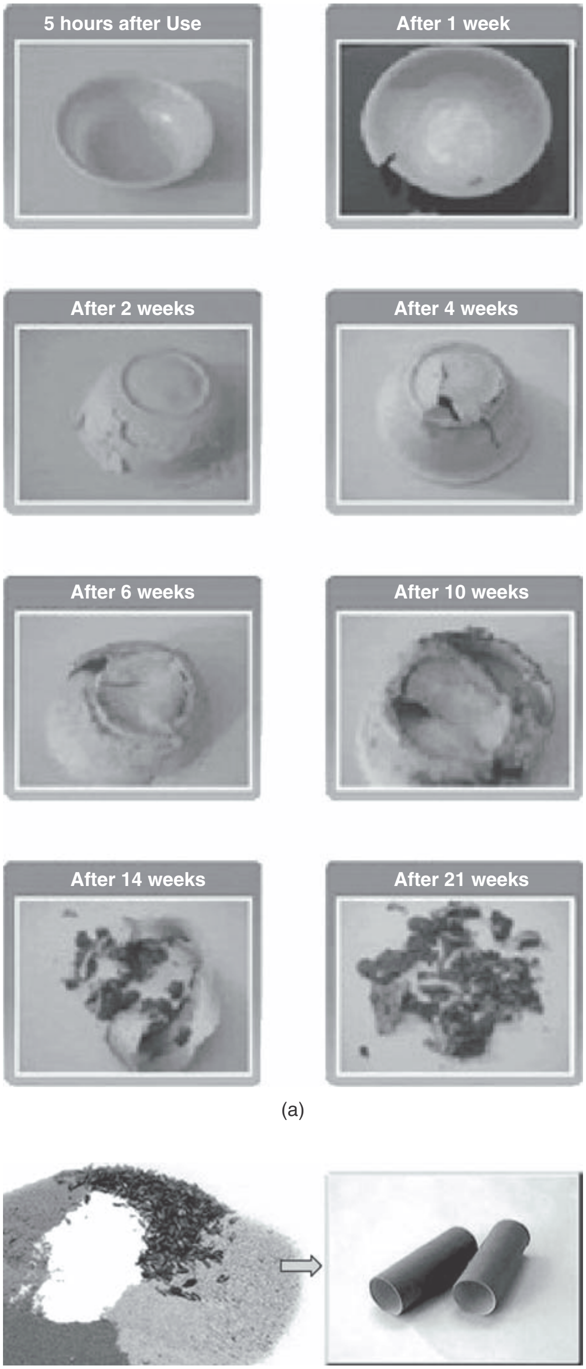
- PLA is made of annually renewable plant resources.
- Fewer fossil-fuel resources are required to produce PLA, resulting in lower greenhouse gas emissions and lower amounts of the air and water emissions associated with traditional plastics.
- PLA is compostable and degrades fully in municipal composting facilities.

Saul identified Agri-Mixx as a potential source derived from plant residue that is biodegradable, pliable, and malleable, is heat resistant to 150°C, and is rigid in structure and hygienic. The rate of the biodegrading process can be controlled in the manufacturing process to range from 12 hours to 18 months upon contact with various fluids. [see Fig. 8.10(a)].

Substituting Agri-Mixx for cardboard as a material for toilet paper rolls provides a biodegradable material when exposed to water, that disintegrates physically. When crushed or broken, it can be composted in a commercial facility or in the backyard [Fig. 8.10(b)].

HUMAN FACTORS AND SUSTAINABILITY

Several students choose to look at what can be termed "human factors" innovations, including strategies for addressing social justice concerns, conceiving government incentive programs to stimulate creation of more sustainable communities by the development community, and authoring educational programs to advance sustainable practices by building awareness and knowledge. One of these projects examined the challenge of collecting and purifying water and the production of palm oil on the African continent and related health concerns given current practices. Junior Civil engineering major Chinyere chose to begin by researching the role of the palm trees native to West Africa, *Elaeis guineensis*, in everything from water collection to medicinal uses. The entire tree plays an important role: from fronds used to cover and protect human-made wells, to palm leaves as a food source for animals and the production of black soap, to palm oil used in cooking, candle production, and lamps, to palm kernels as a



(a)

(b)

Figure 8.10 Products can be made from biogdegradable agricultural residues such as rice husk, sugarcane, and corn. The pulverized fiber composites are held together by naturally occurring starches. (a) The proprietary product Agri-Mixx has the ability to degrade into raw materials of nature and blend into the environment. Under common environmental conditions, it is broken down almost completely in 21 weeks. (b) A student in the Green Engineering and Sustainable Design course at Duke University proposed using such a material as a replacement for the spools around which toilet paper and paper towels are spun.

From Eco Matrix Pte Ltd. http://www.ecomatrix.com.sg/processset.htm, accessed August 22, 2007.

Figure 8.11 In numerous communities, such as this one in Africa, gender roles are quite specific. Merging modern technologies with traditional methods can change the risk profiles for better or worse. For example, in this village, technology can ease women's workload through technological development, but could upset gender roles that have existed for centuries. Technology transfer must always include an appreciation for cultural mores and norms. Even the greenest design is a failure if it is not implemented.

food source for animals and for use in biodiesel fuel, to the pulp used in creating candle wicks. The traditional processes of harvesting palm oil became the focus of Chinyere's innovation, due to the significant health hazards associated with the hand press and boiling methods (see Fig. 8.11) as well as the low yields relative to the amount of labor and time required. The development of a new screw press included the evaluation of alternative indigenous materials and evaluation of their advantages and disadvantages based on material properties. The final solution was drawn from research on techniques developed by the National Institute on Dental and Carniofacial Research. By applying their techniques for developing artificial bones by treating ceramics, a material locally available in the villages from the native clays, an appropriate material for the surface of the new screw press was proposed to replace the fired clays, which proved to be too brittle, and the problems associated with the bamboo surface absorbing the oil.

Elizabeth, a senior mechanical engineering major, sought to build awareness among the entering class of students about the importance of sustainability and the opportunities to be active participants in on-campus programs during their four years of undergraduate study. The "Freshman Sustainability Experience" began with surveys conducted to determine the current knowledge that existed on campus about the 18 programs already in place to collect different types of recyclables. A surprising outcome of this research was the revelation that recycling practices among students actually decreased on campus compared to the level of recycling activity done at home and in high school. The survey data were used to create an action plan for addressing the shortcomings revealed in the current programs as well as creating an orientation for incoming freshman, to build awareness. The action plan included more strategic siting of current recycling opportunities: for example, providing bins in areas at which students gather outdoors. One prominent location is now at "K-Ville," the famous Duke tent community in front of Cameron Indoor Stadium, where students camp out in hopes of receiving basketball tickets. Placing bins appropriate to the type of activity in various buildings on campus (e.g., white paper bins in dorms and computer labs adjacent to printers) was also recommended. Other aspects of the program's design included:

- Letter to incoming freshman with a shopping list emphasizing Energy-Star appliances, compact fluorescent light bulbs, and so on.
- Notification to students on "e-printing" and setting the default to double-sided printing to conserve paper.
- Information on what can be recycled on campus, and where, during move-in.
- The Office of Information Technology sending e-mail notification of the risks of leaving computers on for extended periods of time.
- Easy access to cardboard recycling during move-in.
- Refillable Nalgene water bottles distributed as part of the orientation process.
- During the first few weeks of life on campus, creation of a place outside each dorm to display the quantity of trash being generated and encouragement of competition for reducing the amount of waste, with one bag removed for every bag of recycling (winning dorms being rewarded over the course of the semester with monthly and semester rewards).

The final aspect of Elizabeth's proposal included identification of the costs for implementing the program, which were contained by utilizing existing organizations on campus such as student groups and a small portion of dorm funding for student activities that would be redirected to support the orientation program. In addition to student groups, the support of housekeeping and "Duke recycles" staff would provide willing human resources to advance the program.

SEEING THE FUTURE THROUGH GREEN-COLORED GLASSES

More recently, we have tailored the course to be part of the focused, thematic first-year program at Duke. These students have continously identified new ways to meet the green design challenge. Our colleagues around the nation have shared similar success stories.

The future is in good hands: The next generation is up to the challenge. In fact, many of the givens and assumptions that have shackled previous generations of designers do not weigh heavily on the next generation. They are integrative thinkers. They see the opportunities for closing loopholes and seeking regenerative cycles. They understand the need to build environmental values into design. They are prepared to embrace the regenerative model and are committed to an even brighter future. The future is green—and that is good.

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