6

Green Engineering

For in the true nature of things, if we rightly consider, every green tree is far more glorious than if it were made of gold and silver.
Martin Luther (1483–1546)

What do we as individuals and as a society truly value? In recent years the color green has been a metaphor for environmental consciousness. Why is that? Perhaps it is because when ecosystems are thriving, such as forests and prairies, they exhibit green growth. But green is also a color of pollution, such as the blooms of green algae in eutrophic lakes and ponds, and the growth of green mold on bread. All of these instances, however, do reflect the presence of chlorophyll, the pigment that is part of the energy transformation process, *photosynthesis.* This is the principal means on Earth of storing and converting solar energy into food, which is the energy source for all living creatures. So it makes sense that green represents sustenance from the Earth, hence sustainability.

The two important discoveries that elucidated the photosynthetic pathway were made by Joseph Priestley and Julius Mayer (see their biographical sketchs).

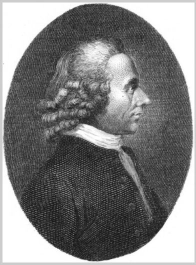
Whatever the reason, green has become recognized as a code for sustainable programs. So a *green engineer* is no longer a term for a neophyte to the profession (opposite of a ‘‘gray beard’’); it is now more likely to mean an environmentally oriented engineer. One of the principles of ‘‘green engineering’’ is a recognition of the importance of *sustainability*.

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.’’[1] The United Nations Conference on Environment and Development (UNCED), 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 (WSSD) identified five major areas that are considered fundamental for moving sustainable development plans forward.

Socially Responsible Engineering: Justice in Risk Management. Daniel A. Vallero and P. Aarne Vesilind

Biographical Sketch: Joseph Priestley



Joseph Priestley (1733–1804) was born in Yorkshire and studied languages, history, and philosophy as a young man. He became a nonconformist in religion, but decided nevertheless to try to earn a living being a preacher. He was singularly unsuccessful, due in part to his stuttering and in part to his unorthodox religious views. He decided to teach at a liberal school, and started to publish books on history, science, and educational theory.

His marriage to Mary Wilkinson forced him to relocate to Leeds, where he once again became a preacher. His house was next to a brewery, which provided him the occasion to conduct experiments on the gases given off during the fermentation of beer. He discovered that the gas (which we now know as CO_2) extinguished lighted wood chips and was heavier than air. If dissolved in water, this gas gave the water a pleasant taste, and Priestley started to serve the drink to his friends, producing the first carbonated beverage.

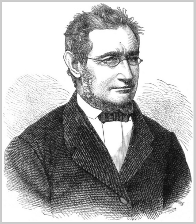
In 1774, Priestley, continuing his experiments with gases, discovered oxygen, unaware that Carl Wilhelm Scheele had made the same discovery a year earlier. In fact, Scheele's experiments referred to "aerial acid" (CO_2) and "fire air" (O_2). Priestley published his work before Scheele, however, and thus received credit for the discovery.

Priestley also gave us a rudimentary understanding of chlorophyll. Conducting experiments on mint plants, he wrote in 1780 that a plant is able to "restore air which has been injured by the burning of candles." In what would today be animal testing, Priestley placed a mouse beneath a glass vessel underwater, so that the only oxygen (Priestley's forte, you will recall) in the glass was available to the mouse. After a few days, he observed that "the air would neither extinguish a candle, nor was it all inconvenient to a mouse which I put into it." Thus, Priestley concluded, the plant was the source of free oxygen.

Priestley was a dissident in many ways, including his opposition to the war in America. After moving to Birmingham, he continued his intemperate preaching, often lauding the goals of the French Revolution and the religious freedom of the United States. This got him driven out of town, and he moved to London. His three sons, meanwhile, had emigrated to the United States, and in 1793, Joseph Priestley followed, moving to central Pennsylvania and establishing a Unitarian fellowship in Northumberland.

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 is to prevent the collapse of the 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 report is silent, however, on just why we should embrace the ideal of intergenerational equity, or why one should be concerned about the

Biographical Sketch: Julius Robert Mayer



The process of photosynthesis was documented by a German surgeon, Julius Robert Mayer (1814–1878), who wrote: ‘‘Nature has put itself the problem of how to catch in flight light streaming to the Earth and to store the most elusive of all powers in rigid form. The plants take in one form of power, light; and produce another power, chemical difference.’’

Like many biological and environmental processes, photosynthesis is deceptively simple; the chlorophyll molecule absorbs sunlight and uses its energy to synthesize carbohydrates from carbon dioxide (CO_2) and water:

$$6CO_2 + 6H_2O \xrightarrow[\text{chlorophyll}]{\text{sunlight}} C_6H_{12}O_6 + 6O_2 \tag{6.1}$$

Also, note the 6 moles of molecular oxygen produced from this reaction, in addition to the carbohydrate (glucose shown).

Mayer was a classic case of good science, yet poor communication. His inability to describe what he did and his apparent unsociability estranged him from the scientific establishment and even caused some to ridicule his findings.

survival of the human species. The goal is a sustainable global ecologic and economic system, achieved in part by the wise use of available resources.

Although this goal has been applied principally at developing nations, sustainable development applies to all human developments. We are creatures that have different needs. Maslow[2] articulated this as a hierarchy of needs, consisting of two classes: basic and growth (see Figure 6.1). The *basic needs* must first 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 first 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 societies that begin to advance 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 engineers will increasingly be called upon to ‘‘build a better world.’’ And, one aspect of ‘‘better’’ is ‘‘sustainable.’’

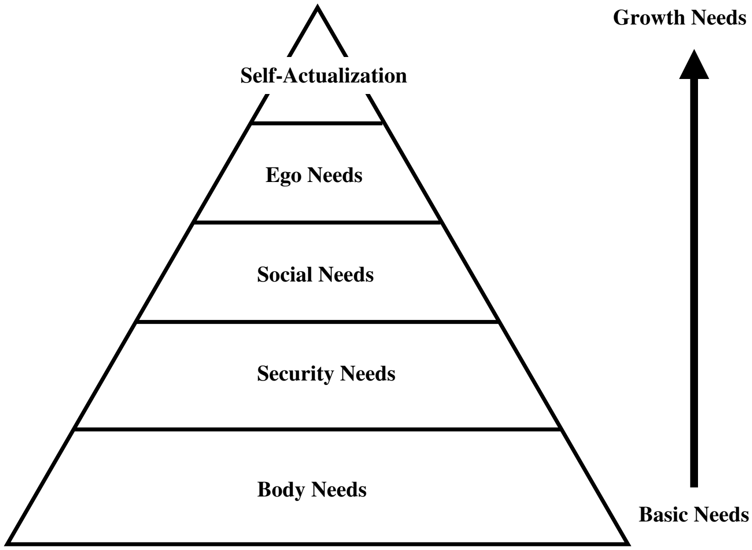


Figure 6.1 Maslow's hierarchy of needs. The lower part of the hierarchy (i.e., basic needs) must first be satisfied before a person can advance to the next growth levels.

Even mechanical engineers, whom we may at first blush think of as being concerned primarily 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 American Society of Mechanical Engineers (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,"[3] 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. On the individual designer scale, the products and processes that engineers design must be considered for their entire lifetimes and beyond.

Hardin's parable demonstrates that even though the person sees the utility of preservation (no new cows) in a collective sense, the ethical egoistic view may well push the decision toward the immediate gratification of the individual at the expense of the collective good. Arguably, this is why we pollute.

FROM GREEN ENGINEERING TO SUSTAINABILITY[5]

To attain sustainability, people need to adopt new and better means of using materials and energy. The operationalizing of the quest for sustainability is defined as *green en-*

Biographical Sketch: Garrett Hardin

Garrett Hardin (1915–2003) received a B.S. in zoology from the University of Chicago and then went to Stanford University where he received his Ph.D. in microbiology. He is best remembered as a curmudgeon—a person who was not afraid to speak what he considered to be the truth, however unpopular the truth might be. In 1968 he wrote a hugely influential article entitled "The Tragedy of the Commons,"[4] which has become a must-read item in every ecology course. 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, whereas the profit will be his alone. So he procures two cows and prospers, but others see this and similarly each wants 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. In other words, systems are elastic up to a point after which they begin to crash. Common goods are particularly vulnerable.

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" pickle of resource of expenditure outstripping availabe resources.

A thread running all through Hardin's books is that ethics has to be based on rational argument and not on emotion. He argues that for ethics to be useful, people have to be literate, they must use words correctly, and they must appreciate the power of numbers. His most interesting book is *Stalking the Wild Taboo,* in which he takes on any number of what he considers to be social misconceptions that demand rational reasoning. Engineers should be careful in applying reason, since the assumptions can drive the expected results. For example, some scientists had argued throughout recent history that the world cannot sustain even half of our present population. Scientific advances have undone some of these assumptions (e.g., improved food supply). On the other hand, engineers should be aware that prudence is essential since resources are finite.

gineering, a term that recognizes that engineers are central to the practical application of the principles sustainability to everyday life. The relationship between sustainable development, sustainability, and green engineering is as follows:

$$\text{sustainable development} \longrightarrow \text{green engineering} \longrightarrow \text{sustainability}$$

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

Green engineering[6] treats environmental quality as an end in itself. The U.S. EPA has defined *green engineering* as ". . . 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."[7]

Green engineering approaches are being linked to improved computational abilities (see Table 6.1) and other tools that were not available at the outset of the environmental movement. Increasingly, companies have come to recognize that improved efficiencies

Table 6.1 Principles of Green Programs

Principle	Description	Example	Role of computational toxicology
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.	Informatics and data mining can provide candidate syntheses and processes.
Safe design	Design products to be fully effective, yet have little or no toxicity.	Using 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 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 up front. 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 nontoxic cleaning products, and is manufactured from renewable resources amenable to being recycled. Upon demolition or reflooring, 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.

Table 6.1 (*Continued*)

Principle	Description	Example	Role of computational toxicology
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.
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 the logic.

Table 6.1 (*Continued*)

Principle	Description	Example	Role of computational toxicology
Nano-materials	Tailormade materials and processes for specific designs and intent at the nanometer scale (≤100 nm).	Emissions, effluent, and other environmental controls; design for extremely long life cycles. Limits and provides better control of production and avoids overproduction (i.e., ‘‘throwaway economy’’).	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, and 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 the range of those found the surface of the sun.[b]

Table 6.1 (*Continued*)

Principle	Description	Example	Role of computational toxicology
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 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: D. A. Vallero, *Paradigms Lost: Learning from Environmental Mistakes, Mishaps, and Misdeeds,* Butterworth Heinemann, Burlington, MA, 2005. First two columns, except "nano-materials," adapted from U.S. Environmental Protection Agency, Green Chemistry, http://www.epa.gov/greenchemistry/principles.html, 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.

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
- 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

There are numerous industrial, commercial, and governmental green initiatives, including Design for the Environment (DFE), Design for Disassembly (DFD), and Design for Recycling (DFR).[8] These are replacing or at least changing pollution control paradigms. For example, the concept of a "cap and trade" has been tested and works well for some pollutants. This is a system where companies are allowed to place a "bubble" over an entire manufacturing complex or to trade pollution credits with other companies in their industry instead of a "stack-by-stack" and "pipe-by-pipe" approach: the *command and control perspective.* 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 higher 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 when 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). Of course, as with all paradigm shifts, expectations must be managed from both a technical and an operational perspective. Not least, the expectations of the client, the government, and those of the individual engineer must be realistic in how rapidly the new approaches can be incorporated.

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, by increasing waste-handling facilities, and if these did not do the job entirely, by limiting rates of production. Green engineering emphasizes 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

Waste reduction involves finding efficient material uses. It is compatible with other engineering efficiency improvement programs, such as total quality management and real-time or just-in-time manufacturing. The overall rationale for waste reduction is that if materials and processes are chosen intelligently at the beginning, less waste will result. In fact, a relatively new approach to engineering is to design and manufacture a product simultaneously rather than sequentially, known as *concurrent engineering*. Combined with DFE and life-cycle analysis, concurrent engineering approaches may allow environmental improvements under real-life manufacturing conditions. However, changes made in any step must consider possible effects on the remainder of the design and implementation.

CASE STUDY: SIDS, A CONCURRENT ENGINEERING FAILURE

One of the most perplexing and tragic medical mysteries of the past 50 years has been sudden infant death syndrome (SIDS). The syndrome was first identified in the early 1950s. Numerous etiologies have been proposed for SIDS, including a number of environmental causes. A recent study, for example, found a statistically significant link between exposure of newborn infants to fine aerosols and SIDS.[9] The study found that approximately 500 of the 3800 SIDS cases in 1994 were associated with elevated concentrations of particle matter with aerodynamic diameters less than 10 micrometers (PM_{10}) in the United States. This estimate is based only on metropolitan areas in counties with standard PM_{10} monitors. Based on the metropolitan area with the lowest particle concentrations, there appears to be a threshold, that is, particulate-related infant deaths occurred when PM_{10} levels were below 11.9 μg m^{-3}.

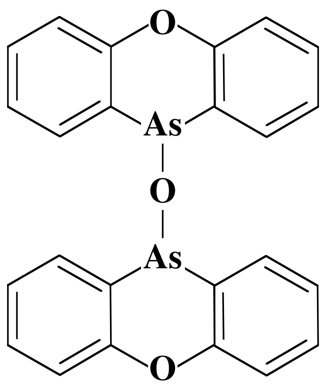
Extrapolations from these data show that almost 20% of all SIDS cases each year in the top 12 most polluted metro areas in the United States are associated with PM_{10} pollution. The number of annual SIDS cases associated with PM_{10} in Los Angeles, New York, Chicago, Philadelphia, and Detroit metropolitan areas range from 20 to 44. The study found that 10 states accounted for more than 60% of the particle-related SIDS cases, with 93 in California, 37 in Texas, and 32 in Illinois.

Since particle matter has been linked to SIDS cases, a logical extension would be to suspect the role of environmental tobacco smoke (i.e., "side-stream" exposure) in some cases, since this smoke contains both particulate and gas-phase contaminants that are released into the infant's breathing zone. Also, in utero exposures to toxic substances when a pregnant woman smokes (e.g., nicotine and other organic and inorganic toxins) may make the baby more vulnerable.

Another suspected etiology for SIDS is the exposure to pollutants via consumer products. For example, polyvinyl chloride (PVC) products have been indirectly linked to SIDS. The most interesting link is not the PVC itself, but the result of an engineering "solution."

Plastics came into their own in the 1950s, replacing many other substances, because of their light weight and durability. However, being a polymer, physical and chemical conditions affect the ability of PVC to stay "hooked together." This can be a big problem for plastics used for protection, such as waterproofing. One such use was as a tent material.

Serendipity often plays a role in linking harmful effects to possible causes. In 1988, Barry Richardson was in the process of renting a tent for his daughter's wedding. While renting a tent from proprietor Peter Mitchell, Richardson, an expert in material science and deterioration, inquired about its durability and found that PVC tents tend to break down. Richardson surmised that the rapid degradation was microbial and in fact due to fungi. The tent manufacturers decided to correct the PVC durability by changing the manufacturing process, that is, by concurrent engineering. In this case, they decided to increase the amount of fungicide, 10,10′-oxybis(phenoxarsine) (OBPA).



10,10′-oxybis(phenoxarsine)

A quick glance at the OBPA structure shows that when it breaks down, it is likely to release arsenic compounds. In this case, it is arsine (AsH_3), a toxic gas (vapor pressure = 11 mmHg at 20°C). It is rapidly absorbed when inhaled, and easily crosses the alveolocapillary membrane and enters red blood cells. Arsine depletes the reduced glutathione content of red blood cells, leading to the oxidation of sulfhydryl groups in hemoglobin and, possibly, red cell membranes. These effects produce membrane instability with rapid and massive intravascular hemolysis. It also binds to hemoglobin, forming a metalloid–hemaglobin complex.[10] These can lead to acute cardiovascular, neurotoxic, and respiratory effects.

Increasing the OBPA to address the problem of PVC disintegration is an example of the problem of ignoring the life-cycle and systematic aspects of most engineering problems. In this case, production and marketing would greatly benefit from a type of PVC that does not break down readily under ambient conditions. In fact, if that problem cannot be solved, the entire camping market might be lost, since fungi are ubiquitous in the places where these products are used.

Had the engineers and planners considered the chemical structure and the possible uses, however, they at least might have restricted the PVC treated with high concentrations of OBPA to certain uses, such as only on tent materials, and not in materials that come in contact with or near humans (bedding materials, toys, etc.). To the contrary, the PVC manufacturers blatantly disregarded the science. Richardson, the expert, from the outset had warned that increasing the amount of fungicide would not only increase the hazard and risk but would make the product less efficacious (even more vulnerable to fungal attack). He stated: “The biocide won’t kill this fungus—instead, the fungus will consume the biocide as well as the plasticizer. Since the biocide contains arsenic, the fungus will generate a very poisonous gas which would be harmful to your staff working with the marquees.” Plasticizers are semivolatile organic compounds (e.g., phthalates) that can serve as a food source for microbes once the microbes become acclimated. The engineers should have known this, since it is one of the biological principles upon which much wastewater treatment is based. But the manufacturers wanted to approach the situation as a linear problem with a simple solution, that is, increase fungicide and decrease fungus. As a kicker, the PVC manufacturer argued that the fungicide was even approved for use in baby mattresses.

The extent to which arsine gas released by the degradation of OBPA was a causative agent in SIDS cases is a matter of debate. But the fact that a toxic gas *could* be released, leading to exposures of a highly susceptible population (babies), is not debatable. Pollution and consumer products are only some of the possible causes of SIDS. Others include breathing position (probably increased carbon dioxide inhalation), poor nutrition, and physiological stress (e.g., overheating).[11]

The overall lesson is that there are many advantages to concurrent engineering, such as real-time feedback between design and build stages, adaptive approaches, and continuous improvement. However, concurrent engineering works best when the entire life cycle is considered. The designer must ask how even a small change to improve one element in the process can affect other steps and systems within the design and build process.

LIFE-CYCLE ANALYSIS

One means of understanding questions of material and product use and waste production is to conduct what has become known as a *life-cycle assessment*. Such an assessment is a holistic approach to pollution prevention by analyzing the entire life 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 environmental impact of a 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 environmental effect of each step in the production, manufacture, use, and recovery/disposal is estimated.

Life-cycle analyses are performed for several reasons, including the comparison of products for purchasing and a comparison of products by industry. In the former case, the total environmental effect of glass-returnable bottles, for example, could be compared to the environmental effect of nonrecyclable plastic bottles. If all of the factors going into the manufacture, distribution, and disposal of both types of bottles are considered, one container might be shown to be clearly superior. In the case of comparing the products of an industry, we might determine if the use of phosphate builders in detergents is more detrimental than the use of substitutes that have their own problems in treatment and disposal.

One problem with such studies is that they are often conducted by industry groups or individual corporations, and (predictably) the results often favor their own product. For example, Proctor & Gamble, the manufacturer of a popular brand of disposable baby diapers, found in a study conducted for them that the cloth diapers consume three times more energy than the disposable kind. But a study by the National Association of Diaper Services found that disposable diapers consume 70% more energy than cloth diapers. The difference was in the accounting procedure. If one uses the energy contained in the disposable diaper as recoverable in a waste-to-energy facility, the disposable diaper is more energy efficient.[12] A lesson here is to use consistent standards and metrics to compare systems.

Life-cycle analyses also suffer from a dearth of data. Some of the information critical to the calculations is virtually impossible to obtain. For example, something as simple as the tonnage of solid waste collected in the United States is not readily calculable or measurable. Even if the data *were* there, the procedure suffers from the unavailability of a single accounting system. Is there an optimal level of pollution, or must all pollutants be removed completely (a virtual impossibility)? If there is both air and water pollution, how must they be compared? This lack of data is particularly problematic when comparing a conventional system that has been in use for decades or centuries to an emerging technology, where only experimental data are available. For example, there is a large disparity of data available for light emitting diode (LED) televisions *versus* the information known about nanotechnologies (e.g., nanotubes) used for the same products.

A recent study supported by the U.S. EPA developed complex models using principles of life-cycle analysis to estimate the cost of materials recycling. The models were able to calculate the dollar cost as well as the cost in environmental damage caused at various levels of recycling. Contrary to intuition and the stated public policy of the U.S. EPA, it seems that there is a breakpoint at about 25% diversion. That is, as shown in Figure 6.2, the cost in dollars and adverse environmental impact start to increase at an exponential rate at about 25% diversion. Should we therefore even strive for greater diversion rates, if this results in unreasonable cost in dollars and actually does harm to the environment?

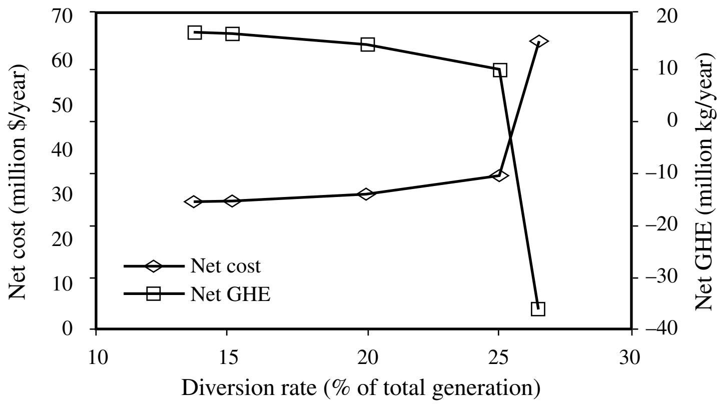


Figure 6.2 The cost in dollars and adverse environmental impact (i.e., greenhouse gas emissions) increases dramatically when the fraction of solid waste recycled exceeds 25%. GHE is greenhouse equivalents, that is, the weighted sum of CO_2 and CH_4 emissions. (From E. Solano, R. D. Dumas, K. W. Harrison, S. Ranjithan, M. A. Barlaz, and E. D. Brill, Integrated Solid Waste Management Using a Life-Cycle Methodology for Considering Cost, Energy, and Environmental Emissions, 2: Illustrative Applications, Department of Civil Engineering, North Carolina State University, Raleigh NC, 2002.)

Discussion: The Coffee Cup Debate

A simple example of the difficulties in life-cycle analysis would be in finding a solution to the great coffee cup debate: whether to use paper or polystyrene coffee cups. The answer most people would give is not to use either, but instead, to rely on the permanent mug. But there nevertheless are times when disposable cups are necessary (e.g., in hospitals), and a decision must be made as to which type to choose.[13] So let's use life-cycle analysis to make a decision.

The paper cup comes from trees, but the act of cutting trees results in environmental degradation. The foam cup comes from hydrocarbon sources such as oil and gas, and this also results in adverse environmental impact, including the use of nonrenewable resources. The production of the paper cup results in significant water pollution, whereas the production of the foam cup contributes significantly less to water pollution. The production of the paper cup results in the emission of chlorine, chlorine dioxide, reduced sulfides, and particulate, whereas the production of the foam cup results in none of these. The paper cup does not require chlorofluorocarbons (CFCs), but neither do the newer foam cups ever since the CFCs in polystyrene were phased out. The foam cup results in the emission of pentane, however, whereas the paper cup contributes none. From a materials separation perspective, the recyclability of the foam cup is much higher than the paper cup since the latter is made from several materials, including the plastic coating on the paper. They both burn well, although the foam cup produces 17,200 Btu/lb (40,000 kJ kg^{-1}), whereas the paper cup produces only 8600 Btu/lb (20,000 kJ kg^{-1}). In the landfill, the paper cup degrades into carbon dioxide (CO_2) and methane (CH_4), both greenhouse gases, whereas the foam cup is relatively inert. Since it is non-reactive, the foam cup will remain in the landfill for a very long time, whereas the paper cup will eventually (but very slowly) decompose. If the landfill is considered a waste storage receptacle, the foam cup is superior, since it does not participate in the reaction, whereas the paper cup produces gases and probably leachate. If, on the other hand, the landfill is thought of as a treatment facility, the foam cup is highly detrimental since it does not biodegrade.

So which cup is better for the environment? If you wanted to do the right thing, which cup should you use? This question, like so many others in this book, is not an easy one to answer. Private individuals can, of course, practice pollution prevention by such a simple expedient as not using either plastic or paper disposable coffee cups but by using a refillable mug instead (although a thorough life cycle analysis would be needed for this option as well). The argument as to which kind of cup, plastic or paper, is better is then moot. It is better not to produce the waste in the first place. In addition, the coffee tastes better from a mug! We win by doing the right thing.

Once the life cycle of a material or product has been analyzed, the next (engineering) step is to manage the life cycle. If the objective is to use the least energy and cause the least detrimental effect on the environment, it is clear that much of the onus is on the manufacturers of these products. The users of the products can have the best intentions for reducing adverse environmental effects, but if the products are manufactured in such a way as to make this impossible, the fault is with the manufacturers. On the other hand, if the manufactured materials are easy to separate and recycle, energy is probably saved and the environment is protected. This process has become known as *pollution prevention* in industry, and there are numerous examples of how industrial firms have reduced emissions or the production of other wastes, or have made it easy to recover waste products and in the process saved money. Some automobile manufacturers, for example, are modularizing the engines so that junked parts can be easily reconditioned and reused, a process known as *design for disassembly* (DFD). Printer cartridge manufacturers have found that refilling cartridges is far cheaper than remanufacturing them, and now offer trade-ins. All of the efforts by industry to reduce waste (and save money in the process) will influence the solid waste stream in the future.

CASE STUDY: THE TRABI

Bad examples of industrial neglect of environmental concerns for the sake of short-term economic gain abound. The use and manufacture of nonrecyclable beverage containers, for example, is perhaps the most ubiquitous example. It might be instructive to establish some baseline of absolutely unconscionable industrial behavior to measure how far we have come in the pollution prevention process. The authors of this book recommend that there be an award established, called the *Trabi Award,* which could commemorate the worst, most environmentally unfriendly product ever manufactured.

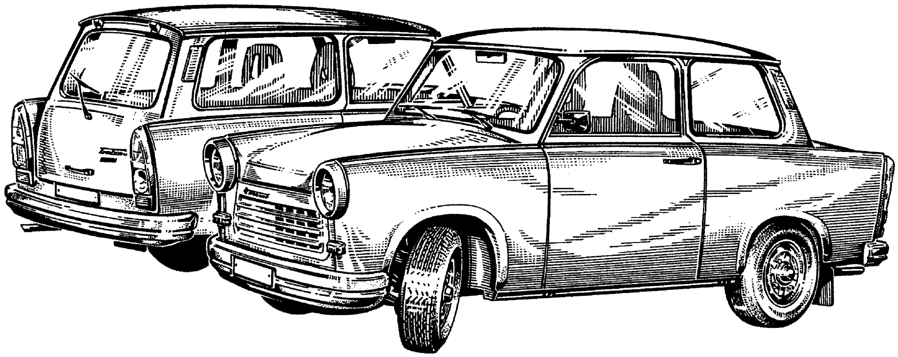


Figure 6.3 The Trabant, an East German car designed without any concern for environmental impact or ease of final disposal.

The Trabant, affectionately known as the Trabi, was manufactured in East Germany during the 1970s and 1980s. This homely-looking car (Figure 6.3) was designed to be the East German version of the Volkswagen (the People's Car), and its design objectives were to make it as cheaply as possible. So, to power the Trabi, the engineers used a two-stroke engine that was notoriously polluting. All of the components were designed at the least cost, and few survived normal use. Worst of all, the body was made of a fiberglass composite that was impossible to fix (except with duct tape, the engineer's cure-all!), and as far as the solid waste management was concerned, had absolutely no recycling value since it could not be melted down or reprocessed in any other way, nor could it be burned in incinerators.

After the reunification of Germany, thousands of Trabis were abandoned on the streets and had to be disposed of in landfills. The Trabi is the best example of engineering design when the sole objective is production cost and when environmental concerns are nonexistent, and the Trabi deserves to be immortalized as the best example ever of environmentally destructive design.

POLLUTION PREVENTION

The present methods of disposing of hazardous wastes are woefully inadequate. All we are doing is simply storing them until a better idea (or more funds, or stricter laws) comes along. Would it be better not to create waste in the first place? That is, why not *prevent* pollution?

The EPA defines *pollution prevention* as the following: "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.''[14] In the widest sense, pollution prevention is the idea of eliminating 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 to make them more readily disposable. Many industries changed to water-soluble paints, for example, thereby eliminating organic solvents, cleanup time, and other expenses 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 for the companies. In addition, the elimination or reduction of hazardous and otherwise difficult wastes has a long-term effect—it reduces the liability the company carries as a consequence of its disposal operations.

With the passage of the Pollution Prevention Act of 1990, the U.S. 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 and promoting 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 all this with the cooperation of the individual 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 alteratives
4. Implement the solutions

These are steps common to any good design. 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. Thus, recognition of the need 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 merely a black box mass balance, using the company as the black box.

Example:

Waste Audit

A manufacturing company is concerned about the air emissions of volatile organic carbons (VOCs). These chemicals can volatilize during the manufacturing process, but there is no way of estimating just how much, or which chemicals. 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 century, referred to as carbon tetrachloride, that the name is still frequently used 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?

Conduct a black box mass balance:

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

where A_{acc} is the mass of A per unit time accumulated, A_{in} is the mass of A per unit time in, A_{out} is the mass of A per unit time out, A_{prod} is the mass of A per unit time produced, A_{cons} is the mass of A per unit time consumed. The materials A are, in this example the three VOCs.

We also need to know the conversion from barrels to cubic meters and the density of each chemical. 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

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

Similarly,

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

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

$$\begin{aligned} A_{out} &= (0.343 \text{ g m}^{-3} \times 0.076 \text{ m}^3 \text{ s}^{-1} \times 86{,}400 \text{ s day}^{-1} \times 365 \text{ days yr}^{-1} \\ &\quad \times 10^{-3} \text{ kg g}^{-1}) + (48 \times 0.12 \times 1548 \times 0.80) + A_{air} \\ &= 822.1 + 7133 + A_{air} \end{aligned}$$

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 conducted for the other chemicals, it appears that the loss to air of methyl chloride is about 16,000 kg yr^{-1} and of the trichloroethylene is about 7800 kg yr^{-1}. If the intent is to cut total VOC emissions, it is clear that the first target should be the methyl chloride, at least in terms of the mass released.

However, as we discuss in Chapters 4 and 5, another approach to preventing pollution is relative risk. Although methyl chloride is two orders of magnitude more volatile, all three compounds are likely to be found in the atmosphere, so inhalation is a probable 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[15] and the inhalation cancer slope factors to represent the hazard. These slope factors for the three compounds are:

$$\text{carbon tetrachloride} = 0.053$$

$$\text{methyl chloride} = 0.0035$$

$$\text{trichloroethylene} = 0.0063$$

Thus, the relative 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: kg · day mg^{-1}, so risk itself includes unitless probability (exposure) (see Chapters 4 and 5). The units of risk are often the number of adverse consequences in a population (e.g., one additional cancer per million or 10^{-6}).

$$\text{carbon tetrachloride} = 0.053 \times 775 = 41$$

$$\text{methyl chloride} = 0.0035 \times 16{,}000 = 56$$

$$\text{trichloroethylene} = 0.0063 \times 7800 = 49$$

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 cancer risk perspective, the importance of removing the three compounds is nearly identical, owing to the much higher cancer potency of CCl_4.

The same approach can be used for non-cancer risk, but rather than using slope factors as the hazard, reference doses (RfDs) and concentrations (RfCs), and average daily doses could represent the potential exposures. Either approach provides a screening or prospective view to aid in pollution prevention.

Once we know what and where the problems are, the next step is to determine useful options. These options fall generally into three categories:

1. Operational changes
2. Materials changes
3. Process modifications

Operational changes might consist simply of better housekeeping, plugging leaks, eliminating spills, and so on. A better schedule for cleaning, and segregating the water might directly yield a large return on a minor investment.

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. Note that this is the same element, Cr, but its oxidative state differs, illustrating the importance of details in sustainable decision-making. 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 were used in air washes to control algal growth. Periodic "blowdown" and cleaning fluids were 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. Fortunately, 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 it eliminated the use of biocides altogether, thus saving the company money. The payback was 1.77 years.[16]

Process modifications usually involve the greatest initial monetary 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 dragout recovery tanks, an intermediate step, has resulted in the savings of the plating solution and reduction in waste generated.

In any case, the most marvelous thing about pollution prevention is that most of the time a company not only eliminates or greatly reduces the discharge of hazardous materials but also saves money. Such savings are in several forms, including of course direct savings in processing costs, as with the ultraviolet disinfection example above. But there are other savings, including the savings in not having to spend time on submitting compliance permits and suffering potential fines for noncompliance. Future liabilities weigh heavily where hazardous wastes have to be buried or injected below ground (a type of ''environmental time bomb''). Additionally, there are the intangible benefits of employee relations and safety. Finally, of course, there is the benefit that comes from doing the right thing, something not to be sneezed at.

MOTIVATIONS FOR PRACTICING GREEN ENGINEERING[17]

To understand the reasons why humans behave as they do, one must identify the driving forces that lead to particular activities. The concept of the driving force can also be used to explain engineering processes. For example, in gas transfer the driving force is the difference in concentrations of a particular gas on either side of an interface. We express the rate of this transfer mathematically as $dM/dt = k(\Delta C)$ where M is mass, t is time, k is a proportionality constant, and ΔC is the difference in concentrations on either side of the interface. The rate at which the gas moves across the interface is thus directly proportional to the difference in concentrations. If ΔC approaches zero, the rate drops until no net transfer occurs. The driving force is therefore ΔC, the difference in concentrations.

Similarly in engineering, driving forces spur the adoption of new technologies or practices. The objective here is to understand what the motivational forces are for adopting green engineering practices. We propose that the three diving forces supporting green engineering are legal considerations, financial considerations, and ethical considerations.

Legal Considerations

At the simplest and most basic level, green engineering is practiced to comply with the law. For example, a supermarket recycles corrugated cardboard because it is the law—either a state law such as in North Carolina, or a local ordinance as in Bucks County, Pennsylvania. This behavior is, at best, ''morality lite.'' Engineers and managers comply with the law because of the threat of punishment for noncompliance. The decision to comply with the law is thus largely a nonmoral decision. Complying with the law is not morally good or morally bad, although not complying may be considered morally bad. So in this situation, managers and engineers choose to do the ''right thing,'' not because it is the right thing to do—but simply because they feel it is their only choice.

We should point out that the vast majority of firms will comply with the law regardless of the financial consequences. Most will not even bother to conduct a cost–benefit analysis because it assumes that breaking the law is not worth the cost.

Occasionally, however, firms may prioritize financial concerns over legal concerns and the managers may determine that by adopting an illegal practice (or failing to adopt a practice codified in law) they can enhance profitability. In such cases they argue that either the chances of getting caught are low or that the potential for profit is large enough to override the penalty if they do get caught (e.g., paying a \$10,000 fine each month is preferred to making a \$10 million upgrade to meet an environmental standard).

For example, in November 1999, the U.S. EPA sued seven electric utility companies: American Electric Power, Cinergy, FirstEnergy, Illinois Power, Southern Indiana Gas & Electric Company, Southern Company, and Tampa Electric Company for violating "the Clean Air Act by making major modifications to many of their coal burning plants without installing the equipment required to control smog, acid rain and soot."[18] On August 7, 2003, "Judge Edmund Sargus of the U.S. District Court for the Southern District of Ohio found that Ohio Edison, an affiliate of FirstEnergy Corp., violated the Clean Air Act's New Source Review (NSR) provisions by undertaking 11 construction projects at one of its coal-fired plants from 1984 to 1998 without obtaining necessary air pollution permits and installing modern pollution controls on the facility."[19] Given the number of violations, it seems obvious that the companies had calculated that breaking the law and possibly getting caught was the least-cost solution and thus behaving illegally was the "right answer." A recent attempt to change such behaviors is that environmental penalty decisions now can include financial advantages gained in noncompliance. The fine will be assessed and additional penalties will be added to make environmental compliance *fair*. Thus, a \$10,000 fine may be increased to \$100,00 if the regulatory agency believes a company gained \$90,000 advantage over their competitors of not complying for the past five years.

In some cases private firms can take advantage of loopholes in tax law that inadvertently allow companies to pretend to be environmentally green while in reality doing nothing but gouging the taxpayer. An example of this is the great synfuel scam.[20] In the 1970s the U.S. Congress decided to promote the use of cleaner fuels in order to take advantage of both the huge coal reserves in the United States and the environmental benefits derived from burning a clean gaseous fossil fuel made from coal. Producing such synfuel from coal had been implemented successfully in Canada, and the U.S. government wanted to encourage our power companies to enter the synfuel business. To promote this industry, Congress wrote into law substantial tax credits for companies that would produce synfuel and defined a *synfuel* as chemically altered coal, anticipating that the conversion would be to a combustible gas that could be used much as natural gas is used today.

Unfortunately, the synfuel industry in the United States did not develop as expected because cheaper natural gas supplies became available. The synfuel tax credit idea remained dormant until the 1990s, when a number of corporations (including some giants like the Marriott hotel chain) found the tax break and went into the synfuel business. Since the only requirement was to change the chemical nature of the fuel, it became evident that even spraying the coal with diesel oil or pine tar would alter the fuel chemistry and that this fuel would then be legally classified as a synfuel. The product of these synfuel plants was still coal, and more expensive coal than raw coal at that, but the tax credits were quite large. Some companies formed specifically to take advantage of the tax break, often with environmentally attractive names such as Earthco, and made huge profits by selling their tax credits to other corporations that needed them. The synfuels industry presently is receiving over $1 billion annually in tax credits, while doing nothing illegal, but also while doing little to benefit the environment.

Financial Considerations

Decisions about the adoption of green practices are also driven by financial concerns. This level of involvement with ''greening'' is at the level promoted by the economist Milton Friedman, who stated famously: ''The one and only social responsibility of business [is] to use its resources and engage in activities designed to increase its profits so long as it . . . engages in open and free competition, without deception or fraud.''[21] In line with this stance, the firm calculates the financial costs and benefits of adopting a particular practice and makes its decision based on whether the benefits outweigh the costs, or vice versa. In fact, this is the most common metric in Western nations for determining whether an activity is acceptable or unacceptable.

Many companies seek out green engineering opportunities solely on the basis of their providing a means of lowering expenses, thereby increasing profitability. Here are some examples[22]:

- In one of its facilities at Deepwater, New Jersey, DuPont uses phosgene, an extremely hazardous gas, and used to ship the gas to the plant. In an effort to reduce the chance of accidents, DuPont redesigned the plant to produce phosgene on site and to use almost all of it in the manufacturing process, avoiding costs associated with hazardous gas transport and disposal.
- Polaroid did a study of all of the materials it used in manufacturing and grouped them into five categories based on risk and toxicity. Managers are encouraged to alter product lines to reduce the amount of material in the most toxic groups. In the first five years, the program resulted in a reduction of 37% of the most toxic chemicals and saved over $19 million in money not spent on waste disposal.
- Dow Chemical challenged its subsidiaries in Louisiana to reduce energy use and sought ideas on how this should be done. Following up on the best ideas, Dow invested $1.7 million and received a 173% return on its investment.

Other firms may believe that adopting a particular green engineering technology will provide them with public relations opportunities: Green engineering is a useful tool for enhancing a company's reputation and community standing. If the result is likely to be an increase in sales for the business, and if sales are projected to rise *more* than expenses, so that profits rise, the firm is likely to adopt such a technology. The same is true if the public relations opportunities can be exploited to provide the firm with expense reductions, such as decreased enforcement penalties or tax liabilities. Similarly, green technologies that not only yield increased sales but decrease expenses at the same time are the perfect recipes for the adoption of green practices by a company whose primary driving forces are financial concerns. For instance:

- DuPont's well-publicized decision to discontinue its $750 million a year business producing chlorofluorocarbons (CFCs) was a public relations bonanza. Not only did DuPont make it politically possible for the United States to become a signatory to the Montreal Protocol on ozone depletion, but it already had alternative refrigerants in the production stage and were able to transition smoothly to these. In 1990, the U.S. EPA gave DuPont the Stratospheric Protection Award in recognition of their decision to get out of CFC manufacturing.[23] The fact that the decision also proved to be highly profitable for DuPont apparently did not matter to the judges.
- The seven electric companies sued by the EPA in November 1999 for Clean Air Act violations (mentioned earlier) heavily publicized their efforts to reduce greenhouse gas emissions. For example, American Electric Power (AEP) issued news releases on May 8, June 11, and November 21, 2002 regarding emissions reduction efforts at various plants. Not coincidentally, the U.S. government, which had sued earlier, was in the process of revising the portions of the Clean Air Act that the company had violated previously. Presumably, regulators were favorably impressed with the company's hard work; in August 2003, the EPA announced that it was dropping the suit and revamping that portion of the act.

These examples clearly demonstrate bottom-line thinking: Cases in which managers were simply trying to practice "good business," seeking ways to increase the difference between revenues and expenses so that profits would rise. As far as we can tell, these decisions were not influenced by the desire to "do the right thing" for the environment. It certainly did not seem to be the *primary* factor. Here we again have examples of non-moral decisionmaking. Businesses are organized around the idea that they will either make money or cease to survive; in the "financial concerns" illustrations provided so far, green practices were adopted as a means of making more money.

On occasion, though, managers are *forced* into considering the adoption of greener practices by the threat that not doing so will cause expenses to rise and/or revenues to fall. For example, in October 1998, ELF (Earth Liberation Front) targeted Vail Ski Resort, burning a $12 million expansion project to the ground.[24] In the wake of this damage, the National Ski Areas Association (NSAA) began developing its Environmental Charter in 1999 with "input from stakeholders, including . . . environmental groups"[25] and officially adopted the charter in June 2000.[26] In accordance with the charter, NSAA has produced its Sustainable Slopes Annual Report each year since 2001.[27] Apparently, the driving force behind the decision to adopt the Environmental Charter was largely a response to financial concerns rather than by the desire to treat the environment responsibly—it was a non-moral decision. That is, NSAA was spurred to create the Environmental Charter by concerns about member companies' bottom lines: Further "ecoterrorist" activity could occur, thereby causing expenses to rise; and the ELF action may have sufficiently highlighted the environmental consequences of resort development to the point that environmentally minded skiers might pause before deciding to patronize resorts where development was occurring, thereby causing revenues to fall. Incidentally, the act of ELF is considered by many ethicists to be *immoral;* that is, unethical means to achieve an end that the group sees as a higher value.

Similarly, for firms trying to do business in Europe, adopting ISO 14000 is close to a required management practice. The ISO network has penetrated so deeply into business practices that firms are nearly locked out if they do not gain ISO 14000 certification.

There is ample evidence that one of the reasons businesses participate in the quest for sustainability is because it is good for business. The leaders of eight leading firms that adopted an environmentally proactive stance on sustainability were asked in one study to justify the firms' adoption of such a strategy.[28] All companies reported that they were motivated first by regulations such as the control of air emissions, pretreatment of wastewater, and the disposal of hazardous materials. One engineer in the study admitted that ''the [waste disposal] requirements became so onerous that many firms recognized that benefits of altering their production processes to generate less waste.''

The second motivator identified in this study was competitive advantage. Lawrence and Morell quote one director of a microprocessor company, who noted that ''by reducing pollution, we can cut costs and improve our operating efficiencies.'' The company recognized the advantage of cutting costs by reducing its hazardous waste stream.[29]

Another study, conducted by PriceWaterhouse Coopers, confirmed these findings.[30] When companies were asked to self-report on their stance on sustainable principles, the top two reasons for adopting sustainable development were found to be (1) enhanced reputation (90%), and (2) competitive advantage (cost savings) (75%). It is not clear if the respondents were given the option of responding that they practiced sustainable operations because this was mandated by law. If it had, there is no doubt that all companies would have publicly stated that they are, indeed, law abiding.

So it seems likely that the two primary driving forces behind the adoption of green business and engineering practices are (1) legal concerns and (2) financial concerns. Can we argue that such behavior is morally admirable simply on the basis that the outcomes (e.g., cleaner air and water) are morally preferable? We say no. In accord with Sethi,[31] we argue instead that actions undertaken in response to legal and financial concerns are actually *obligatory,* in that society essentially demands that businesses make their decisions within legal and financial constraints. For an action to be morally admirable, however, the motivating force driving the decisions has to be far different in character.

Ethical Considerations

The first indication that some engineers and business leaders are making decisions where the driving force may not be due to legal or financial concerns comes from several cases in American business. Although most business or engineering decisions are made on the basis of legal or financial concerns, some companies believe that behaving more environmentally responsibly is simply the right thing to do. They believe that saving resources, and perhaps even the planet, for the generations that will follow is an important part of their job. When making decisions, they are guided by the ''triple bottom line.'' Their goal is to balance the financial, social, and environmental impacts of each decision.

A prime example of this sort of thinking is the case of Interface Carpet Company.[32] Founded in 1973, its founder and CEO until 2001 was Ray Anderson, now chairman of the board. By the mid-1990s, Interface had grown to nearly $1.3 billion in sales, employed some 6600 people, manufactured on four continents, and sold its products in over 100 countries worldwide. In 1994, several members of Interface's research group asked Anderson to give a kick-off speech for a task force meeting on sustainability; they wanted him to provide Interface's environmental vision. Despite his reluctance to do so—

Anderson had no ‘‘environmental vision’’ for the company except to comply with the law—he agreed. Fortuitously, as Anderson struggled to determine what to say, someone sent him a copy of Paul Hawken’s *The Ecology of Commerce*[33]; Anderson read it, and it completely changed not only his view of the natural environment, not only his vision for Interface Carpet Company, but his entire conception of business. In the coming years, he held meetings with employees throughout the Interface organization explaining to them his desire to see the company spearhead a sustainability revolution. No longer would they be content to keep pollutant emissions at or below regulatory levels. Instead, they were going to strive to be a company that created zero waste and did not emit any pollutants *at all*. The company began to employ ‘‘The Natural Step’’[34] and notions of ‘‘Natural Capitalism’’[35] as part of its efforts to become truly sustainable. The program continues today, and although the company has saved many millions of dollars as a result of adopting green engineering technologies and practices, the reason for adopting these principles was not to earn more money, but rather, to do the right thing.

Yet another example is that of Herman Miller, an office furniture manufacturing company located in western Michigan. Its pledge in 1993 to stop sending any materials to landfills by 2003 has resulted in the company’s adoption of numerous progressive but sometimes expensive practices. For example, the company ceased taking scrap fabric to the landfill and began shredding it and trucking it to a firm in North Carolina that processes it into automobile insulation. This environmentally friendly process costs Herman Miller \$50,000 each year, but the company leaders agree that a decision that is right for the environment is the right decision. Similarly, the company’s new waste-to-energy plant has increased costs, but again company leaders feel that it is worth the cost, as employees and managers are proud of the company’s leadership in preserving the natural environment in their state.[36]

Our point here is this: The decisions made by the leadership of Interface Carpet Company and Herman Miller were not morally admirable simply because they enabled these companies to reduce toxic emissions (among many other positive outcomes for the environment); they were morally admirable because the *driving force* behind those decisions was the desire to stop harming the Earth, to protect it so that future generations would be able to enjoy it as much as, or even more than, we do today. Conversely, in the cases of DuPont, Polaroid, and Dow Chemical cited earlier, the *driving force* behind their decisions to adopt green technologies was a desire to save the company money; the benefits to the Earth were simply an ancillary by-product of those decisions.

THE MORAL CHALLENGE OF GREEN ENGINEERING[37]

We identify three primary driving forces behind corporate decisions to adopt green engineering practices: legal, financial, and ethical considerations. Most firms do not even consider disobeying the law. Legal concerns are their top priority. Financial concerns are nearly as high on the priority scale: Managers consider it their duty to shareholders or owners to assure that the company makes an adequate profit, so they base decisions about green practices on a cost–benefit analysis of the probable consequences. These firms are not concerned with ‘‘doing the right thing’’ except inasmuch as the ‘‘right thing’’ means obeying the law and making money. In other words, these firms may decide to adopt green engineering and business practices strictly on the basis of legal and financial factors, without being significantly influenced by the desire to protect the natural environment. Only when the driving forces involve the desire to do good for all people do such decisions become moral in character.

This observation suggests that it might be possible to develop a normative model of green engineering. Such a normative view would ask the question: What *ought* to be the driving forces for adopting green engineering practices? Our proposed normative model is rooted in the work of developmental constructivist thinkers such as Kohlberg,[38] Piaget,[39] Rest,[40] and others 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 the 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. And 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[41]) 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. These seem to be particularly critical regarding moral judgment: A person's ability to make moral judgments tends to grow with maturity as they pursue further education, generally reaching its final and highest stage of development in early adulthood. This theory of moral development is illustrated by Kohlberg's stages of moral development:

Pre-conventional level

1. Punishment–obedience orientation
2. Personal reward orientation

Conventional level

3. ''Good boy''–''nice girl'' orientation
4. Law and order orientation

Post-conventional level

5. Social contract orientation
6. Universal ethical principle orientation

Kohlberg insisted that these steps are progressive. He noted that in the two earliest stages of moral development, which he combined under the heading *pre-conventional 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 *post-conventional stage,* wherein they have an even broader perspective. Their moral decision making is guided by universal moral principles[42]: that is, by principles that reasonable people would agree should bind the actions of all people who find themselves in similar situations.

We propose that the 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 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. And 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 green engineering behavior. This normative model of green engineering can be illustrated as shown in Figure 6.4.

There is a striking similarity between Kohlberg's model of moral development and the model of moral green engineering. Avoiding punishment in the moral development model is similar to a corporation staying out of trouble by obeying the law. The pre-conventional level and our legal concern level have similar driving forces.

At the second level in the moral development model is a concern with peers and community, while in our model the corporation undertakes green business practices in order to make more money for the stockholders and to provide a service or product for their customers that will in turn make the corporation more profitable. At this level, as in the previous one, self-centeredness and personal well-being govern decisions.

Finally, at the highest level of moral development, a concern with universal moral principles begins to govern actions, while for the corporate model, fundamental moral principles having to do with environmental issues control corporate decisions. In both of these cases the driving force or motivation is trying to do the right thing on a moral (not legal or financial) basis.

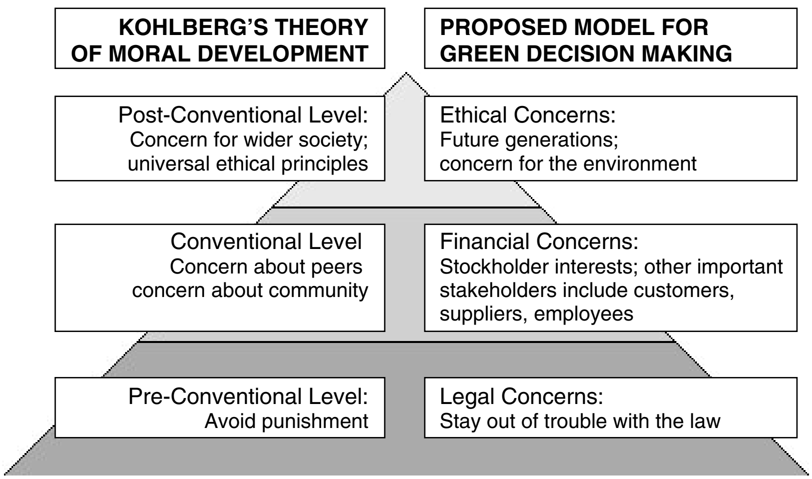


Figure 6.4 Model for understanding the motivations for green decision making. (From P. A. Vesilind, L. Heine, and S. Hamill, Kermit's Lament: It's Not Easy Being Green, *ASCE Journal of Professional Issues in Education and Engineering,* Forthcoming.)

We suggest that moral green engineering occurs only when engineers and managers base their decisions about the adoption of green business and engineering principles on ethical considerations. That is, they recognize the broad impact that their decisions may have, and they act in such a way that their actions will be in the best interest not only of themselves, their companies, and their companies' direct stakeholders, but also the broader society and even future generations.

Green engineering will eventually lead the world to sustainability, but green engineering today occurs most often when doing the right thing also results in adherence to laws and regulations and in achieving greater profitability for the organization. This kind of green engineering, although often beneficial to society, is more business acumen than morally admirable.

The true heroes of green engineering are those leaders who believe deeply in the principles of green engineering and who try to work within these principles while still helping their corporations to be profitable. They enjoy working to promote sustainability, and do so not for show or profit but because it gives them pleasure to do the right thing.

FUTURE PEOPLE

One of the unique characteristics of humans is that we have self-awareness. We can see ourselves in the world today, and we know that humans existed in days gone by, and our species will (we hope) exist tomorrow. We thus are able to plan for the future and accept delayed gratification.

But there will come a time in the future where we individually are long dead and we can no longer personally benefit from any actions that we might have taken on our own behalf. For that matter, there will come a time, after our death, when we are not longer burdened by the ill-considered actions that might have led to unhappiness. Why, then, worry about the future?

We can, based on empirical evidence, assume that there will be a future, of some sort, and we have some confidence that this future will be inhabited by human beings. It is this future—the future without you and me—that we now address.

Although the ''client'' for engineers is almost always an existing person or organization, the work in which engineers engage can have far-reaching consequences for persons who are not yet born: future people. It is easy to argue that engineers have a moral responsibility to existing people by virtue of their position in society, but does this extend to these future persons, those as yet unborn, who may or may not even exist?

We believe that there are two reasons why the engineer has moral responsibilities to future people:

- Many engineering works, be they small gadgets or huge buildings, will certainly last for more than one generation and will be used by people who were not yet born when the product or facility was constructed.
- Engineers can and do appreciably alter the environment, and the health, safety, and welfare of future people will depend on maintaining a sustainable environment.

Engineers conceive, design, and construct products and facilities that last for generations. Indeed, many engineering decisions have no effects until decades later. For example, suppose that engineers choose to dispose of some hazardous waste in steel containers buried underground. It may take generations for waste containers to corrode, for their contents to leach, for the leachate to migrate and pollute groundwater, and for toxic effects to occur in people coming in contact with the water. Such a problem is not of concern for present people since it will be decades before the effects are felt. The only persons to be adversely affected by such an engineering decision are future people, and they are the only ones who have no say in the decision.

Some would argue that we owe no moral obligations to future generations because they do not exist and the alleged obligation has no basis because we do not form a moral community with them. This is a fallacious argument, however. Even if future generations do not yet exist (by definition), we can still have obligations to them. If we agree that we have moral obligations to distant peoples whom we do not know, it would be reasonable to argue that we have similar moral obligations to people who are yet unborn.

Vesilind and Gunn[43] use an analogy to illustrate this point. Consider a terrorist who plants a bomb in a primary school. Plainly the act is wrong, and in breach of a general obligation not to cause (or recklessly risk) harm to fellow citizens. Even though the terrorist may not know the identities of the children, we would all agree that this is an evil act. And the same would be true if the terrorist bomb had a very long fuse, say 20 years. This would be equally heinous, even though the children, at the time the bomb was placed, had not yet been born. Some engineering works, such as the hazardous waste disposal alluded to above, have very long fuses, and there is no doubt that future people can be harmed by irresponsible engineering activities. The act of burying wastes in the ground where they will not find their way to drinking water supplies for some decades is no different from the act pouring the wastes down a well, except in terms of time.

The second way that engineers have responsibility to future generations is by consciously working to maintain a sustaining environment. Global warming is one instance where the damage done to date is so severe that the effects will not be felt until many years from now. Most models predict that by building up greenhouse gases at the present time, the temperature of the Earth will be slowly getting warmer even if and when we begin to reduce the emission of such gases. This is analogous to heating a pot of water on an electric stove. The burner is turned on and the water begins to heat. When the burner is turned off the temperature of the water does not drop immediately to room temperature. The burner is still warm, heat continues to be transmitted to the pot, and the temperature of the water continues to rise even after the burner is turned off. This effect will also occur with global warming (although rather than heat being buffered, the decrease in the concentrations of greenhouse gases will resist change even after the sources are removed). We therefore may have already exceeded the level of sustainability with regard to the Earth's temperature but we will not know about it until decades from now.[44]

Some argue that we have no obligation to maintain a good-quality environment for future generations because we cannot know what kind of an environment they will want. Our sole responsibility to future generations is therefore not to plan for them.[45]

But this is a hollow argument. Just like the Vestal Virgin who was buried alive with only a little bread and water, we know very well that future generations will *not* want contaminated air or water, dramatically reduced number of species, or global warming. Certainly, there will be changes in style and fashion, and future generations will no doubt have different views on many of our present moral issues, but we also know that they will want a sustainable environment for themselves and their children. Irreparable global warming, or large-scale radiation, or the destruction of the ozone layer are not, under any circumstances, what our progeny would want. Parents do not know what careers their children will choose when they grow up, whom they will marry, or what their lifestyle will be like, but the parents *do* know that their children will want to be healthy, and thus the parents are morally obligated to provide heath care for their children. Also, future generations probably will not want to suffer genetic damage or to produce babies with severe birth defects, and thus our obligation to them is to control chemical pollution. The argument that because we don't know the desires of future people, our only obligation is to not plan for them is therefore wrong.

The engineers' responsibilities to society are the control and prevention of pollution, and they are therefore entrusted to help maintain a healthy environment. Because this responsibility extends into the future, the ''public'' in the first canon in the codes of ethics should refer to all people, present and future.

The future, therefore, is the future beyond the careers of present engineers. But unlike some laborers or tradespeople, the effect of their work will last long after they are no longer around. Is it important to you, today, to know that what you do will have a positive effect on future people? Sustainability is, afterall, a temporal concept since we do now will have lasting effects.

The profession and practice of engineering is changing, but we will always be required to have strong analytical skills. The engineer of the future will increasingly need ''practical ingenuity'' as well as the ability to find new ways of doing things (i.e., creativity) built on a framework of high ethical standards, professionalism, and lifelong learning.[46] These are the qualities of a *good* engineer. New tools are becoming available to assit us, such as computational methods (e.g., toxicology and fluid dynamics), quantitative structural activity relationships (QSARS), and ever-improving preductive models.

Although the Viking society of northern Europe was in many ways cruel and crude, they had a very simple code of honor. Their goal was to live their life so that when they died, others would say ''He was a good man.'' The definition of what they meant by a ''good man'' might be quite different by contemporary standards, but the principle is important. Conversely, the Talmudic precautions regarding the ''sins of the fathers'' suggests the chaotic (e.g., ''Butterfly Effect'') of today's decisions. If we live our professional engineering lives so as to uphold the exemplary values of engineering, the greatest professional honor we could receive would be to be remembered as a *good* engineer.

REFERENCES AND NOTES

1. World Commission on Environment and Development, United Nations, *Our Common Future,* Oxford Paperbacks, Oxford, 1987.
2. A. Maslow, *Motivation and Personality,* 2nd ed., Harper & Row, New York, 1970.
3. American Society of Mechanical Engineers, Professional Practice Curriculum: Sustainability, http://www.professionalpractice.asme.org/communications/sustainability/index.htm, accessed November 2, 2004.
4. G. Hardin, Tragedy of the Commons, *Science,* 162:1243–1248, Dec. 13, 1968.
5. This section is based on a paper originally authored by P. A. Vesilind, L. Heine, J. R. Hendry, and S. A. Hamill.
6. The source for this discussion is S. B. Billatos and N. A. Basaly, *Green Technology and Design for the Environment,* Taylor & Francis, Bristol, PA, 1997.

7. U.S. Environmental Protection Agency, What Is Green Engineering? http://www.epa.gov/oppt/greenengineering/whats_ge.html, accessed November 2, 2004.
8. See S. B. Billatos and N. A. Basaly, *Green Technology and Design for the Environment,* Taylor & Francis, Washington, DC, 1997; and V. Allada, Preparing Engineering Students to Meet the Ecological Challenges Through Sustainable Product Design, *Proceedings of the 2000 International Conference on Engineering Education,* Taipei, Taiwan, 2000.
9. T. J. Woodruff, J. Grillo, and K. C. Schoendorf, 1997, The Relationship Between Selected Causes of Postneonatal Infant Mortality and Particulate Air Pollution in the United States, *Environmental Health Perspectives*, 105(6), June 1997.
10. R. E. Gosselin, R. P. Smith, and H. C. Hodge, *Clinical Toxicology of Commercial Products,* 5th ed., Williams & Wilkins, Baltimore, 1984.
11. Since we brought it up, the SIDS Alliance recommends a number of risk reduction measures that should be taken to protect infants from SIDS:
    - *Place your baby on his or her back to sleep.* The American Academy of Pediatrics recommends that healthy infants sleep on their backs or sides to reduce the risk for sudden infant death syndrome (SIDS). This is considered to be most important during the first six months of age, when baby's risk of SIDS is greatest.
    - *Stop smoking around the baby.* SIDs has long been associated with women who smoke during pregnancy. A new study at Duke University warns against use of nicotine patches during pregnancy as well. Findings from the National Center for Health Statistics now demonstrate that women who quit smoking during pregnancy, but resume after delivery, put their babies at risk for SIDS, too.
    - *Use firm bedding materials.* The U.S. Consumer Product Safety Commission has issued a series of advisories for parents regarding hazards posed to infants sleeping on top of beanbag cushions, sheepskins, sofa cushions, adult pillows, and fluffy comforters. Waterbeds have also been identified as unsafe sleep surfaces for infants. Parents are advised to use a firm, flat mattress in a safety-approved crib for their baby's sleep.
    - *Avoid overheating, especially when your baby is ill.* SIDS is associated with the presence of colds and infections, although colds are not more common among babies who die of SIDS than babies in general. Now research findings indicate that overheating too much clothing, too heavy bedding, and too warm a room may greatly increase the risk of SIDS for a baby who is ill.
    - *If possible, breastfeed.* Studies by the National Institutes of Health show that babies who died of SIDS were less likely to be breastfed. In fact, a more recent study at the University of California–San Diego found breast milk to be protective against SIDS among nonsmokers but not among smokers. Parents should be advised to provide nicotine-free breast milk if breastfeeding, and to stop smoking around your baby, particularly while breastfeeding.
    - *Mother and baby need care.* Maintaining good prenatal care and constant communication with your health care professional about changes in your baby's behavior and health are of the utmost importance.
12. Dy-Dee Diaper Service, http://www.dy-dee.com/, accessed April 22, 2005.
13. M. S. Pritchard, *On Being Responsible,* University Press of Kansas, Lawrence KS, 1991.
14. U.S. Environmental Protection Agency Pollution Prevention Directive, May 13, 1990, quoted in H. Freeman et al., Industrial Pollution Prevention: A Critical Review, presented at the Air and Waste Management Association Meeting, Kansas City, MO 1992.
15. Even without calculating the releases, is probably reasonable to assume that the exposures will be similar since the three compounds have high vapor pressures (more likely to be inhaled): carbon tetrachloride, 115 mmHg; methyl chloride, 4300 mmHg; trichloroethylene, 69 mmHg.
16. S. Richardson, Pollution Prevention in Textile Wet Processing: An Approach and Case Studies, *Proceedings: Environmental Challenges of the 1990's,* EPA/66/9-90/039, U.S. EPA, Washington, DC, September 1990.

17. Much of this discussion appeared in an earlier paper, ‘‘Ethics of Green Engineering’’ by P. A. Vesilind, L. Heine, J. R. Herndry, and S. A. Hamill.
18. C. Lazaroff, U.S. Government Sues Power Plants to Clear Dirty Air, *Environment News Service,* http://ens.lycos.com/ens/nov99/1999L-11-03-06.html, 1999.
19. D. Fowler, 2003, Bush Administration, Environmentalists Battle over ‘‘New Source Review’’ Air Rules, *Group Against Smog and Pollution Hotline,* Fall 2003, http://www.gasp-pgh.org/hotline/fall03_4.html, accessed January 3, 2004.
20. D. L. Barlett and J. B. Steele, The Great Energy Scam, *Time,* 162(15):60–70, October 13, 2003.
21. M. Friedman, *Capitalism and Freedom,* University of Chicago Press, Chicago, 1962, p. 133.
22. K. Gibney, Sustainable Development: A New Way of Doing Business, *Prism* (American Society of Engineering Education), January 2003.
23. Billatos and Basaly, note 6.
24. J. Faust, 2004, Earth Liberation Who? ABCNEWS.com Web site, http://more.abcnews.go.com/sections/us/DailyNews/elf981022.html, accessed January 3, 2004.
25. National Ski Areas Association, Environmental Charter, http://www.nsaa.org/nsaa2002/_environmental_charter.asp, 2002.
26. J. Jesitus, Charter Promotes Environmental Responsibility in Ski Areas, *Hotel and Motel Management,* 215(19):64, 2000.
27. National Ski Areas Association, Sustainable Slopes Annual Report, http://www.nsaa.org/nsaa2002/_environmental_charter.asp?mode=s, 2002.
28. A. T. Lawrence and D. Morell, Leading-Edge Environmental Management: Motivation, Opportunity, Resources and Processes, in *Research in Corporate Social Performance and Policy,* J. E. Post, D. Collins, and M. Starik (Eds.), Supplement 1, JAI Press, Greenwich, CT, 1995.
29. Lawrence and Morell, note 28.
30. PriceWaterhouse Cooper, *Sustainability Survey Report*, PWC, New York, August 2002.
31. S. P. Sethi, Dimensions of Corporate Social Performance: An Analytical Framework, *California Management Review,* 17(3):58–64, Spring 1975.
32. R. C. Anderson, *Mid-Course Correction—Toward a Sustainable Enterprise: The Interface Model,* Peregrinzilla Press, Atlanta, GA, 1998.
33. P. Hawken, *The Ecology of Commerce: A Declaration of Sustainability*, Harper Business, New York, 1994.
34. See K.-H. Robért, 1991, Educating a Nation: The Natural Step, *In Context,* 28, Spring 1991. According to their website (http://www.naturalstep.org/): ‘‘Since 1988, The Natural Step has worked to accelerate global sustainability by guiding companies, communities, and governments onto an ecologically, socially, and economically sustainable path. More than 70 people in 12 countries work with an international network of sustainability experts, scientists, universities, and businesses to create solutions, innovative models, and tools that will lead the transition to a sustainable future.’’
35. A. B. Lovins, L. H. Lovins, and P. Hawken, A Road Map for Natural Capitalism, *Harvard Business Review,* 7(3):145–158, 1999.
36. L. T. Hosmer, Herman Miller and the Protection of the Environment, in *The Ethics of Management.* McGraw-Hill Irwin, Boston, 2003.
37. An earlier version of this discussion appeared as ‘‘Ethical Motivations for Green Business and Engineering’’ by P. A. Vesilind and J. R. Hendry. *Clean Technology and Environmental Policy*.
38. L. Kohlberg, *The Philosophy of Moral Development,* Vol. 1, Harper & Row, San Francisco, CA, 1981.
39. J. Piaget, *The Moral Judgment of the Child,* Free Press, New York, 1965.
40. J. R. Rest, *Moral Development: Advances in Research and Theory,* Praeger, New York, 1986; and J. D. Rest, D. Narvaez, M. J. Bebeau, and S. J. Thoma, *Postconventional Moral Thinking: A Neo-Kohlbergian Approach,* Lawrence Erlbaum Associates, Mahwah, NJ, 1999.

41. R. Duska and M. Whelan, *Moral Development: A Guide to Piaget and Kohlberg,* Paulist Press, New York, 1975.
42. J. A. Rawls, *A Theory of Justice.* Harvard University Press, Cambridge, MA, 1785; and I. Kant, *Foundations of the Metaphysics of Morals,* translated by L. W. Beck (1951), Bobbs-Merrill, Indianapolis, IN, 1959.
43. P. A. Vesilind and A. S. Gunn, *Engineering, Ethics, and the Environment,* Cambridge University Press, New York, 1998 p. 39.
44. This is one of the hottest topics of debate in environmental circles. It is not our purpose here to take one side or another, but *if* the predictions are correct, the most dramatic and harmful effects would be in the coming decades. Our point is that even with the gaps in knowledge, these effects would only be avoided by prudent decisions now. After the warming has reached severity, several decades of recovery may well be needed to reach a new chemical and energy atmospheric equilibrium. This dilemma is the thrust behind the *precautionary principle,* that is, if the potential harm is sufficiently severe the prudent course of action is to avoid the action. However, in some decisions, the precautionary principle does not work well, such as the current debate regarding potential environmental impacts from emerging technologies (e.g., nanotechnology). Simply not allowing advancing technologies is unsatisfying since society would lose the benefits (i.e., *opportunity risks*), including environmental and public health benefits (e.g., improved sensors, sentinel systems, treatment of cancer, and improved waste site clean-up).
45. M. Golding, Obligations to Future Generations, *Monist,* 56:85–99, 1972.
46. National Academy of Engineering, *The Engineer of 2020: Visions of Engineering in the New Century,* National Academies Press, Washington, DC, 2004.