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Technology and Environment: An Overview

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Be content at least with the verdict of time, which reveals the hidden defects of all things, and, being the father of truth and a judge without passion, is wont to pronounce always, a just sentence of life or death.

Baldesar Castiglione, The Book of the Courtier, *1528*

What will be the verdict of time on the man-made world? Uneasiness prevails in our newspapers, political forums, and cities; in the forests; and beside the lakes and oceans. Many feel that economic, technological, and scientific developments are accompanied by ever-larger risks for environment, society, and health. With each year, unanticipated and unintended consequences of mature technologies reveal themselves more clearly and long after a commitment to the technologies has suffused the economy: the greenhouse effect from fuels that warm and transport us; the hole in the ozone layer from chemicals that cool our refrigerators and make worries about safe and convenient home food supply a dim memory of grandparents; lung cancer associated with asbestos fibers that were a breakthrough a few decades ago for fireproofing ships, schools, and office buildings. It is equally feared that emerging technologies, such as the genetic engineering of new organisms, will release more problems than they solve. Yet, traditional optimism remains widespread that innovations will be found to finesse or counteract harmful environmental consequences of the ways we transform the planet. Will the verdict on our realization of technology in the environment be life, "sustainable development of the biosphere," or the decay and self-destruction that is one of the futures always envisioned for humankind?

This book seeks to contribute toward answering this question. It articulates what Paul Gray calls the paradox of technology, that environmental disruption is brought about by the industrial economy, but that advancement of the industrial economy has also been and will be a main route to environmental quality. The book examines several analytic frameworks for exploring interactions of technology and environment. It includes review of the history of environment as affected by technology. It offers several technological opportunities to reduce or bypass both current and forecast environmental problems. It provides discussion of social and institutional aspects of the question, for example, how education and the professions must change to play more positive roles in environmental matters. This opening chapter synthesizes the contributions that follow and seeks to place in perspective the relationship between technology and the environment that is the subject of the volume.

Perhaps it is best at this early stage to remind ourselves of some of our technological successes with respect to environment in the broadest sense. It is technology, above all, that has denied or forestalled the original Malthusian vision of population outrunning subsistence. Mankind has been able to modify and increase the size of its niche and sustain increasing population at higher levels of economic well-being. That niches keep changing, through the introduction of new technologies, and that we can change them are too commonly overlooked. For example, systems of transportation and energy have arisen over the past two centuries that would have been unimaginable, given a static definition of resources and unchanging policy with regard to disposal of wastes. The problem of typhoid was largely solved by chlorination of municipal water supplies, although private well owners waited a long time to adopt this solution. In the industrialized world, air and especially water in numerous urban areas are cleaner and safer than a century, or even a couple of decades, ago.

The contemporary question is whether humans may now be so threatening the boundary conditions of the earth system that our technological tool kit will not suffice. Are we infinite or are we reaching closure? We pushed back the North Sea and built more than half the land that is today the Netherlands. Now we wonder whether we dare push nature any further. We drained the malarial marshes of the Maremma on the Italian coast to make them humanly habitable. Now we define global habitability to include many species besides our own.

We must also recognize that many environmental problems have not proven to be as serious as originally forecast. Public alarms about mercury in swordfish, pesticides in cranberry bogs, and radiation from Three Mile Island are among numerous examples. The lesson from these episodes is not that we should distrust all news of environmental dangers, but rather that the public wants a sense of security.

Then what do we learn when we search the history of environment and technology for guidelines? Generally in the industrialized countries, ways have been devised to accommodate and prepare the way for economic growth and increases in population density without decline of key measures of environmental quality and health. Will our ingenuity, technical and social, match current and future needs?

In fact, as Thomas Lee and other authors point out in this volume, both resources and environment are functions of technology. Concerns about scarce resources have repeatedly subsided as technology expanded the available reserve or provided alternatives. According to Lee, the pressure for closure of the system stems more properly from concerns about the capacity of the environment as a receptacle for wastes than from its bounty of resources. It is rarely true that depletion of resources is the driving force for resource substitution. From a historical perspective, energy substitution, for example, has been driven by the availability of a set of new technologies that enabled an alternative energy source to satisfy better and at an acceptable cost the end-use demand of society.

It is useful at this point to distinguish several sources of environmental problems. Some problems come about largely because of irresponsible or unintelligent behavior. Careless ship operations appear to be the immediate cause of the *Valdez* oil spill in Alaska; oil leaks from drilling in the Santa Barbara Channel off California in 1970 could very likely have been prevented by more thorough geological studies and better engineering practice. Some problems arise because of collective effects of individual behavior that is not particularly serious on a small scale or in a forgiving geographical context. The smog of Los Angeles is caused by the sum of a multitude of actions that might be permissible elsewhere, but not in the Los Angeles basin with its enclosing mountain ranges, prevailing westerly winds, and large concentration of people and vehicles. Other problems arise simply out of ignorance. No environmental impact statement at the time of the innovation is likely to have identified the problems that arose decades later with DDT or chlorofluorocarbons (CFCs). Electric refrigeration looked like a marvelous advance over the icebox when it was introduced into the mass market in the late 1920s, and the CFCs looked attractive compared with the problems of leaks and explosions associated with ammonia and other first-generation coolants. Certainly no chemist could have been expected in the 1930s to link CFCs to destruction of stratospheric ozone, which could not be measured accurately at that time, or to the greenhouse effect, then a theory discussed only in the most hypothetical terms by basic scientists interested in the earth's geological history.

In the United States, as Victoria Tschinkel describes, there has been a tendency to treat all kinds of problems the same way, litigiously, and to use a great deal of social effort in attributing effects to causes and assigning blame. It is necessary to recognize better in the U.S. administrative and legal systems that one is not necessarily a horrible individual if one truly did not understand certain things. This volume makes the point strongly that the essence of the environmental crisis is not nearly so much bad actors as the whole, often contradictory, structure of incentives of the economy. Given how complete definition of environmental problems has become (see Table 1), perhaps in the United States for many environmental matters it is time to think more broadly and pragmatically in terms of a "no-fault" society. There is a need to shift from negative to positive reinforcement and to reduce the expense and time involved in resolving disputes. Products and incentives should be designed in such a way that a minimum of hazardous waste is created, but also, it should be easy to dispose of those wastes that are created; society might better use its resources to buy and recycle these materials than to prosecute those who dump them.

A no-fault orientation does not deny the existence of criminality or conflict. On the contrary, we must accept that there are often genuine conflicts of interest on environmental issues, conflicts between industrial and neighborhood objectives or between local and global interests. However, it is becoming rarer for a purely local solution to endure. Globally approaching environmental closure means that, increasingly, we must seek policies that are consistent at all levels of the system and internationally, for example with regard to waste disposal or greenhouse gas emissions.

A no-fault orientation also does not diminish attention to the roles and responsibilities of industry. However, as this volume makes clear, environmental analysis and regulation have sometimes tended to focus on industry as the major force shaping the evolution of the environment to the exclusion of other important forces. And, we have tended to view industry as a collection of pollution sources. As pointed out by Robert Ayres, Sheldon Friedlander, and Robert Herman and coauthors, this view is inadequate. We must be at least as concerned with the environmental consequences of consumption. First we looked at factories, then at some of their products. Now we must encompass the entire system of production and consumption, the metabolism of our society, in our analyses and policies.

FRAMEWORKS FOR ANALYSIS

In Part 1 of this book, the authors advance three ways of approaching the definition and assessment of environmental problems. The concept of *industrial metabolism* leads to more unified, continuous, and comprehensive consideration of production and consumption processes from an

TABLE 1 Selected Environmental Problems

1. Urban air pollution
2. Regional air pollution, including acid rain
3. Hazardous or toxic air pollutants
4. Indoor radon
5. Indoor air pollutants other than radon
6. Radiation other than radon
7. Depletion of stratospheric ozone associated with CFCs and other substances
8. Global climate change associated with carbon dioxide and other greenhouse gases
9. Water pollution associated with direct and indirect point source discharges from industrial and other facilities to surface waters
10. Water pollution associated with nonpoint source discharges to surface waters
11. Contaminated sludge
12. Pollution of estuaries, coastal waters, and oceans from all sources
13. Deterioration of wetlands from all sources
14. Pollution of drinking water as it arrives at the tap from chemicals, lead in pipes, biological contaminants, and radiation
15. Pollution of groundwater and soil at hazardous waste sites, both sites with continuing disposal and those no longer in use
16. Pollution of groundwater and other media at nonhazardous waste sites, including municipal landfills and industrial sites
17. Exhaustion of landfills
18. Groundwater contamination from septic systems, road salts, injection wells, leaking storage tanks, and other sources
19. Wastes and tailings from mining and other extractive activities
20. Accidental releases of toxic substances
21. Oil spills and other accidental releases of environmentally damaging materials or substances
22. Pesticide residues on foods eaten by humans and wildlife, and risks to applicators of pesticides
23. Risks to air and water from pesticides and other agricultural chemicals as a result of leaching and runoff, aerial spraying, and other sources
24. New toxic chemicals
25. Undesirable environmental release of genetically altered materials
26. Exposure to consumer products
27. Worker exposure to chemicals
28. Reductions in biodiversity
29. Deforestation and desertification

NOTE: These environmental problems can be grouped or ranked according to a variety of criteria, for example, scale (local to global); whether the problems relate primarily to human health or to ecosystems; carcinogenicity; extent to which technical solutions are currently available; and economic costs.

SOURCE: After U.S. Environmental Protection Agency (1988).

environmental point of view. The question of *dematerialization* forces reconsideration of the origins and solutions of environmental issues and places proposals for waste reduction and recycling in context. The examination of *long-term regularities in technological development* provides quantitative evidence of the role of technology in the evolution of environmental problems and offers some optimism about prediction of future problems and their solutions. All of these frameworks might be regarded as elements of a more complete *industrial ecology*, examining the totality or pattern of relations between economic activity and the environment (Frosch and Gallopoulos, 1989).

As described by Ayres, industrial metabolism encompasses both production and consumption, the entire system for the transformation of materials, the energy and value-yielding process essential to economic development. Application of the industrial metabolism viewpoint involves detailed accounting of the flows of materials and energy through human activities. It has yielded a number of important insights.

One insight is that in many places the major human sources of environmental pollutants have been shifting from production to consumption processes. Several industries have increasingly been able to control the materials flows in their production processes quite comprehensively. The history of the chemical industry, for example, is in considerable part one of finding new uses for former waste products. It is probably safe to say, according to Ayres, that industry in the next century will recycle or use a number of today's major tonnage waste products, notably sulfur, fly ash, and lignin waste from paper manufacture.

A second insight is that a large number of materials uses are inherently dissipative. Many materials are degraded, dispersed, and lost (to the economy) in the course of a single normal use. In addition to fuels and food, this applies to many packaging materials, lubricants, solvents, flocculants, antifreezes, detergents, soaps, bleaches and cleaning agents, dyes, paints and pigments, most paper, cosmetics, pharmaceuticals, fertilizers, pesticides, and herbicides. Most of the current consumptive uses of toxic heavy metals, such as arsenic, cadmium, chromium, and mercury, are dissipative in this sense. Other uses are dissipative in practice because of the difficulty of recycling such items as batteries and electronic devices. Increasing product and materials complexity may also contribute to a tendency toward dissipative use, because recycling may become inherently more difficult with complexity.

Thus, although it is important to ask whether in some ways the environmental system is reaching closure, it is also important to recognize that often what must be traced are pathways that are not cycles in a meaningful sense. Although materials do not leave system boundaries, many follow a unique, nonrepetitive evolution on human time scales, combining, recombining, and moving. According to Ayres, more than 90 percent of the total mass of environmentally "active" materials processed annually are converted into waste almost as fast as extracted. It would be useful to develop measures of dissipation and sort out more clearly what can be described accurately as cyclical and what cannot. Finally, it is clear that a significant fraction of materials streams arising from consumptive, dissipative uses is not regularly monitored or perhaps amenable to monitoring. A new vocabulary is needed, emphasizing transformation, transport, and redeposition, and perhaps new indices of dilution and concentration.

From a policy point of view, there are several important consequences of the metabolism perspective. Already noted is the need to attend more to consumption and to develop new concepts for monitoring. Another point is that an effect of dispersion and dissipation of materials is to make problems global. Although problems of production may tend to be industrial and local, problems of consumption will tend to be problems for everyone and global. Ayres also points out that, whereas residuals tend to disappear from the market domain, where everything has a price, they do not disappear from the natural world in which the economic system is embedded. Thus, many signals given by prices are wrong from an environmental viewpoint. For example, differences in prices of coal, oil, and gas scarcely reflect the different environmental consequences of these energy sources.

Industrial metabolism is not a complete model, but it is clearly a useful heuristic device. It makes us more sensitive to comprehensive examination of sources, transport, and fate of pollutants and can lead to earlier identification of problems and a broader range of monitoring, including technological and socioeconomic trends, as well as traditional environmental indicators. It would be desirable to extend the detailed case studies of industrial metabolism beyond those already performed on cadmium and chromium to several other "metabolically active" elements. A need and potential exist for a more systematic look at the material and energy flows of alternative industrial metabolisms, for example, one centered more on use of hydrogen as an energy carrier. The metabolic metaphor is also useful in that it spurs us to think jointly of the health of the ecological and human systems and to look for diseases and treatments. Modifications are clearly needed to increase reliance on regenerative and sustainable processes and to increase efficiency with regard to production and use of by-products.

The term *dematerialization*, explored by Robert Herman, Siamak Ardekani, and Jesse Ausubel, is employed to characterize the decline over time in weight of materials used in industrial end products, or in the "embedded energy" of the products. Dematerialization would be tremendously important for the environment, because less material could translate into smaller quantities of waste generated in both production and consumption. Statements about trends toward dematerialization have been made casually, and these authors seek to provide a systematic basis on which to identify the forces and measures that would allow a credible statement to be made about dematerialization.

There are widely held perceptions of a long-term trend of decline in weight (intensity) of materials and energy embodied in a range of end-use services. Among the evidence pointed to are the decline in per capita consumption of such basic materials as steel in some advanced industrialized countries and the increasing efficiency of energy use. The significant decline in use of steel in the automotive industry does provide strong evidence in support of dematerialization in production. Further evidence of dematerialization in production is provided by data on overall industrial solid waste generation, which showed a significant decline for several years beginning in 1979.

However, the overall picture about dematerialization is not so sanguine. Generation of municipal solid waste has been on the increase, and there appears to have been overall a linear increase in discards with time measured by weight. The potential factors that are offsetting the efficiency gains are numerous. If smaller, lighter products are also inferior in quality, then more units would be produced and the net result could be a greater amount of waste generated. Spatial dispersion of the population is a potential materializer. Migration from urban to suburban areas, often driven by affluence, requires more roads, more single unit dwellings, and more automobiles. The shift from larger families to smaller nuclear families may be a materializer. So may be such activities as photocopying and advertising; the high cost of repair; styles, fashions, and fads; and product innovation. Of course, economic and population growth are major underlying forces.

Herman and coauthors review a number of examples, including the effect of the information revolution on materials demand and waste. Contrary to expectation, the information revolution has led to a significant materialization, especially with respect to paper. In 1959 it was believed that 5,000 Xerox machines would saturate the U.S. market. Instead, in the information era, trees are at risk.

Considerably smaller amounts of waste are generated by most countries with incomes comparable to the United States. The difference is often attributed to more serious effort to recover and reuse wastes, but in fact the differences are not well sorted out. Moreover, the question of dematerialization interacts in complex ways with objectives for system closure or recycling. For example, substituting plastics for steel in a car may reduce weight and increase fuel efficiency but also decrease possibilities for recycling of materials. A question of utmost importance remaining to be addressed is that of rates and styles of materialization of the three-quarters of the world's population in developing countries.

The concept of dematerialization forces evaluation of economic growth in terms that are significant for numerous environmental problems, especially those associated with solid wastes. Like industrial metabolism, dematerialization shows the relative unimportance of production processes per se. The traditional view has been that what leaves the factory gate is good. Dematerialization directs industry and all of society to be more concerned about the eventual fates of its manufactures. It confronts us with the question of whether society can truly afford to continue functioning in its present "throwaway" mode of products such as diapers, batteries, paper, and beverage containers. It suggests that perhaps minimum volume over a product life cycle should be an environmental design criterion, along with factors such as toxicity, and that incentives must be found for cradle-to-grave materials monitoring and responsibility.

Ausubel shows intriguing, though still tenuous, evidence of long-term regularities in the evolution, diffusion, and replacement of several families of technologies that are critical to the environment, including energy, transportation, and materials. Many diffusion processes appear to occur according to a rather strictly set clock. Regular behavior is exhibited over a range of time scales, but what is most impressive is the steady evolution of large systems over periods of many decades. Ausubel does not comment on causes of the behavior but simply points out that the evidence of significant regularities in technological change is increasingly well established.

An example is in pulses of growth in use of energy lasting 40 years or more. There have been at least two of these: one evidently stretching coal to its limits as a fuel and a subsequent pulse in which oil exhausted many of its opportunities in the market. It may be speculated that during each pulse the leading source of energy supply reaches environmental and other constraints that limit the overall growth of the energy system. In other words, a characteristic density of use may be all that is achievable or socially tolerable for each source of energy within the context of the larger industrial paradigm in which that source of energy dominates. To accommodate further increases in per capita energy consumption, each time it is necessary for a society to shift to a source of primary energy that is not only economically sound but also more environmentally compatible and in some ways more efficient, especially in transport and storage.

More generally, the focus on long-term evolution of technology highlights many remarkably positive aspects of the performance of engineering with respect to resources and environment over the past century. Series of innovations have been brought forth to escape what appeared to be insoluble problems of shortages of resources (such as wood for railroad ties) or overburdening of the assimilative capacity of the environment (for example, waste from the growth of the population of horses in cities around the turn of the century).

The existence of long-term regularities may have predictive value if we observe them early enough and can estimate their characteristics. Ausubel's chapter suggests that an era may be under way in which it is possible to predict with greater accuracy and reliability the emergence of environmental problems. It might provide new perspectives for setting priorities among environmental problems. The questions would be, What technologies are most promising in light of what is understood about overall trajectories of technological development? Can policies be implemented that will enhance the diffusion of selected technologies? How quickly and to what extent can technologies be deflected from well-established trajectories?

Together, the three related frameworks for analysis described above promise to provide a much stronger foundation for our understanding of the technological sources of environmental change. Such a foundation is essential for development of projections of future loading of the environment in which we have more confidence. These projections increasingly form the basis of both social regulation and environmental research.

SOME SOLUTIONS

In Part 2, Richard Balzhiser and Thomas Lee propose some technological contributions to solutions of environmental problems associated with energy production and consumption. There is general agreement that reduction in emissions from the supply side and improvement in efficiency on the demand side are the right things to do. For the supply side, the technological tool kit appears to be well stocked, for example, to burn coal much more cleanly to alleviate problems of acid rain. Indeed, the record of engineering achievement shows sustained improvement in thermal efficiency accompanied by a continuing decline in the cost of electricity over most of the century. In the past few years, energy requirements and losses associated with stringent emission controls have offset continued engineering improvements aimed at efficiency.

An immediate task is to find the next generation of technology that exploits a basically different systems approach to clean coal combustion. However, this may be only a local or short-run solution, because it may increase the carbon dioxide emissions associated with global climate warming. From this point of view, natural gas is the most convenient fuel of choice for addition and replacement of electricity-generating capacity for the next decade.

Gas is clean and available, and it minimizes exposure to financial risk in investment. It is convenient and also quick to install in relatively small increments for either utility or nonutility generation and for cogeneration. At current prices and with available technology gas is the option of economic choice in the United States not only for peaking but also for middle-range and some base-load applications. It offers the prospect of continuing technical advances in the lifetime and efficiency of gas turbines and in combined gas-steam cycle systems.

From the perspective of long-term regularities in the energy system, gas also appears to be the fuel of choice. It is on a vigorous trajectory toward increased market share. Moreover, gas technology is still young. For years, natural gas was a by-product of oil exploration. Only recently have many wells been drilled intentionally for gas exploration. Effectiveness in gas exploration is growing by use of satellite remote sensing and ground truth measurements, and drilling technologies are advancing underground to greater depth with increased speed and accuracy.

To optimize further use of coal as well as gas resources, the integrated gasifier with combined cycle (IGCC) can be considered a major step forward. If carbon dioxide must eventually be removed from power plant effluents, IGCC can probably best accommodate this requirement, not without cost, but at costs below other coal-based alternatives. Meanwhile, gas produces less carbon dioxide per kilowatt-hour than any other fossil fuel option and permits us some time to understand better the issue of climate change without imposing costly but ineffectual carbon dioxide removal requirements.

At present, the United States seems to be adding boundary conditions to the energy industry in such a way that Balzhiser predicts market shares of primary energy sources for generating electricity will remain almost perfectly static as far as the year 2020. This seems a most unlikely development, given the patterns of change over the past 100 years. Moreover, no one believes that the United States is now at an economic or environmental optimum in the energy sector. However, Balzhiser points out that most energy decisions in the United States are being postponed, only small incremental changes are being made, and thus the key choices are arising by default. As with the rest of the aging national infrastructure, the United States is taking the energy infrastructure for granted and living off investments of the past. In this circumstance, extension of plant lifetimes has become one of the most important engineering challenges. This involves both sensor technologies and computer aids that give much broader coverage of equipment with on-line diagnostics.

Lee and Balzhiser envision an evolution of the energy system to one that integrates energy into a system of materials processing, a realization of the "metabolic" view proposed by Ayres. It might begin as a marriage of coal and gas technologies and evolve ultimately into fully "integrated energy systems" (IES). The IES concept is one in which product streams and energy streams merge. The increasing orientation of power plants toward chemical process is taken seriously in all dimensions. Coal, crude oil, liquefied petroleum gases, and natural gas could all be primary materials used by the system. For example, natural gas would be used as a fuel in heaters, as a feedstock, or as a fuel for making hydrogen. Intermediate industrial gases are exploited to their maximum benefit. The entire steam system of the facility is integrated and, in turn, integrated with the electric system. Waste of heat or components is minimized, thereby enhancing economic efficiency. Zero emission, the ultimate dream for energy systems, as Lee points out, can be accomplished only with a hydrogen economy, and IES offers a technological road toward that goal.

Depletion of the ozone layer is another illustrative tale of technology and environment, as described from the perspective of U.S. industry by Joseph Glas. Chlorofluorocarbons were invented around 1930 as a safe alternative to ammonia and sulfur dioxide for use in home refrigerators. The intent was to eliminate the toxicity, flammability, and corrosion concerns of the other chemicals by developing a stable chemical with the right thermodynamic properties. That effort was so successful that the new compounds were also quite easy to make and rather inexpensive. New applications for a safe class of chemicals with the properties of CFCs were plentiful, and the market blossomed. Currently, virtually all refrigeration, commercial air-conditioning, defense and communications electronics, many medical devices, and high-efficiency insulation use CFCs in some way. But today, more than 50 years after the development of CFCs, we have modified and extended our definition of "safe."

It now seems likely that CFCs will be largely phased out over the next 10–20 years, and it is the development of new technologies that has provided what appear to be viable options for meeting society's demands simultaneously for caution on environmental modification and for the services provided by CFCs. In the extreme, a ban on CFCs before alternative chemicals or technologies can be put into place would be damaging both to safety and to economics. Moreover, it would almost certainly be ineffective. Unified action and implementation on a global scale are needed, and bans in the absence of alternatives would likely lead to uncontrollable, uncooperative behavior both by producers still seeing a market opportunity and by consumers wanting a service.

In the ozone story, the rate of technological progress and the degree of risk are inextricably related. It is a story that promises a gratifying outcome, with science, governments, and industry acting forcefully by building on common goals of protecting the environment and agreeing on technical analyses.

SOCIAL AND INSTITUTIONAL ASPECTS

Why is the promising story of stratospheric ozone protection not repeated more often? A key reason, articulated by Tschinkel in Part 3, has been the inadequacy of individual professions in the face of complex problems and an equal difficulty among key groups in making common cause. As Tschinkel describes, a succession of professions in the United States has discovered environmental problems over the past 100 years: first physicians and experts in public health, then engineers, later biologists and toxicologists, and most recently lawyers. Each discovered problems and offered solutions. All of the solutions have had unforeseen consequences, whether natural, social, or economic, and most have been so narrowly focused that opportunities to achieve larger public goals have been missed or obscured.

Given the elusiveness of assigning causes, predicting effects, and finding cures for many environmental problems, it is not surprising, as Tschinkel points out, that the United States has developed a condition ripe for the legal profession to flourish in. In the past 20 years the legal system has generated some of the key decisions supporting environmental protection. As Tschinkel contends, it has also produced an adversarial, combative climate in which it is virtually impossible for people from industry to discuss facts with their colleagues in government or the public. We "are constantly in litigation and constrained from solving problems by using each other's talents cooperatively." Moreover, the litigation is often not fruitful. For those environmental cases that went to trial in federal civil courts, 10 percent took longer than 67 months to resolve. Most serious, according to Tschinkel, the legalistic approach has produced a staggering load of regulations that leaves little time or incentive for creativity and human judgment in developing solutions and no time for concentrating on environmental results. It has created a process-oriented, rather than a results-oriented, approach in a sector where the result, namely, environmental quality, is what we seek and need.

In fact, the succession of legislative activities has resulted in an enormous, sometimes contradictory, uncoordinated patchwork of control requirements for smoke, air and water pollution, solid wastes, and noise, as well as aesthetics. An example is that U.S. regulations require advanced waste treatment of domestic waste at about 50 percent higher cost than the usual secondary treatment when discharged into a eutrophic water body. Next to this "gold-plated pipe" is often found a storm water ditch carrying the equivalent of raw sewage: the water that flows through it receives absolutely no treatment. What strategy makes sense in this situation for technologists and, indeed, for society as a whole? On the one hand, better engineering would create fewer problems for biologists and lawyers to worry about; on the other hand, imaginative approaches are needed to foster cooperative activity between technical experts and the policymaking community.

As Friedlander stresses, the technological community, indeed all of society, has been largely reactive to environmental issues. In the past we have tended to wait for crises, as Walter Lynn chronicles, and then responded. Society needs a positive agenda for environment, based on more comprehensive theories, better data bases, and better analyses. For engineers, the emphasis should be on design of environmentally compatible technologies, both for manufacturing and plant operations and for products. The latter must be accented, while evidence grows that environmental consequences of consumer products may be more important than the direct effects of industrial activity, as demonstrated by the perspectives of industrial metabolism and dematerialization.

Design should not merely meet environmental regulations; environmental elegance should be part of the culture of engineering education and practice. Selection and design of manufacturing processes and products should incorporate environmental constraints and objectives at the outset, along with thermodynamic and economic factors. Ever-increasing goals for environmental quality present the engineering profession with challenges in design, basic research, and education.

Environmental engineering must become a more integral part of chemical, manufacturing, materials, and other engineering fields, not only civil engineering, to which it is traditionally closest. Environmental quality must become a pervasive ethic in all engineering design. In turn, values must be transformed into engineering requirements—values about preservation of ecosystems and biota, protection of public health, and intergenerational responsibility. In Gray's words, "the great hope and the great challenge before us are to bring engineering education and practice, industrial priorities, and public policy into alignment in ways that eliminate the paradox of technological development."

Over the past few years, as described by Friedlander, a movement has grown stressing design and in-plant processes, in contrast to add-on devices or exterior recycling, to reduce or eliminate waste. This movement has been called waste reduction or pollution prevention. Current regulatory practices focus almost exclusively on what comes out of the pipe or smokestack. They ignore broader systems-oriented approaches and the assimilative capacity of the environment, and impose lockstep application of selected technologies.

End-of-the-pipe approaches will provide few further benefits. We need first to prevent waste creation. This involves the development of substitute products and processes emphasized by Ausubel and reengineering much of what is done in key industries. We should seek general principles to guide the search for substitutes for certain broad classes of widely used materials with environmental effects. As mentioned by Friedlander, in response to developing regulatory trends and competition from the paper industry, the chemical industry in the United States and Europe has begun development of biodegradable plastics, much as was done 25 years ago, when long-lasting detergents were polluting water bodies.

It is important to gain acceptance of the primacy of reducing waste and preventing waste creation. The primacy rests on several factors, identified by Friedlander. Avoiding the creation of a waste eliminates the need for its treatment and disposal, both of which carry environmental risk. Control technologies may fail or fluctuate in efficiency. Treated effluent streams carry nonregulated residual substances that may turn out later to be harmful. Secured disposal sites eventually discharge into the environment.

Methods of waste reduction include in-plant recycling, changes in process technology, changes in plant operation, substitution of input materials, and modification of end products both to permit use of less-polluting upstream processes and to prevent the products themselves from becoming problem wastes. According to Friedlander, the technology of waste reduction does not yet have a widely accepted scientific basis. There is a need to find a class of generic scientific and engineering principles that will eventually make it possible, in the words of Tschinkel, for the concept of treatment to become passé.

In the meanwhile, it is desirable to follow a clear hierarchy in waste management (Science Advisory Board, 1988). If waste cannot be prevented, then we should seek to recycle or reuse it. However, recycling may have acquired a level of visibility as a potential solution that exceeds its promise. Apart from behavioral and economic hurdles, recycling faces technical limitations. For example, recycling paper shortens paper fibers and lowers quality. There are precious metals, such as platinum and rhodium used in catalytic converters, that industry would like to recycle, but an economic means to collect the converters has not yet been found. It must, moreover, be recognized that many recycling sites have subsequently become "Superfund" sites, where cleanup activities are required.

If recycling or reuse is not possible, then it is time for treatment and destruction, relying on technologies such as bioremediation and incineration. If those options are insufficient, the next resort is waste isolation, for example, well-constructed sanitary landfills. The last resort is avoiding exposure to released residues. It is important to point out that even with waste reduction, incineration, and recycling, no landfills will remain in a couple of decades or sooner for many major population concentrations. Globally, and especially in the industrialized countries, we are faced with our own materialization, a culture that in the United States produces some 5 to 10 pounds of waste per capita per day, depending on the comprehensiveness of definition of the term. Even with remarkable engineering achievements, many of the problems associated with waste disposal will become worse.

Although it may not be possible to represent fully costs relating to health and ecosystems in economic terms, a key need is the economic data base to support decision making about waste reduction and alternatives.

Even in a prominent case like automotive tires, there is no strong analytic base for evaluating the relative merits of gradual decomposition versus burning or smelting. More effort is required to calculate the true costs of waste disposal options, including potential liability costs.

TECHNOLOGICAL OPPORTUNITIES

In general there is a need to identify, research, and put into practice high-leverage areas of innovation for environmental quality. Already mentioned is the need for biodegradable plastics; more could be understood about using ultraviolet radiation or gamma rays to irradiate and harmlessly decompose plastics. Materials research itself can be a key to dematerialization. More needs to be understood about incineration and combustion; progress on fundamentals of combustion is already enabling the design of engines that produce lower NO_x emissions. Microbial transformation of wastes, for example, selective removal of heavy metals, offers promise. It is time to become serious about technologies for reducing and recycling carbon dioxide emissions. Technologies for cost-effective separation of hydrogen remain areas of potentially high environmental payoff. There are also pervasive needs for improvement and deployment of monitoring technologies. Environmental monitoring remains labor intensive and based on technologies that should soon be superseded by new sensors and measurement methods.

As Gray argues, the growing concentrations of greenhouse gases in the atmosphere logically lead to a reconsideration of the possibility of increasing the use of nuclear energy. Gray proposes that we develop, build, and test radically different reactor designs that pose negligible risks of the accidental release of radioactive materials as a result of overheating. Several possibilities exist, including new water-cooled and liquid-metal-cooled designs, as well as gas-cooled designs. These hold the promise of passively safe operation. The nuclear question is a reminder that many engineering systems have been poorly designed from the point of view of operators and that this human aspect of design must be taken more seriously, whether in electrical or chemical plants, supertankers, or consumer products.

One of the most interesting questions is that of research and market opportunities with regard to efficiency, especially energy efficiency. In the past few years there has been a shift among many environmentalists to a revised view of the "soft path" option that emphasizes managing demand downward rather than supply upward to meet societal needs and problems. The revised view emphasizes efficiency but omits life-style changes that were part of the soft path program in the 1970s.

Still, why is efficiency gaining much less than predicted and espoused? There may be several answers. One is almost certainly the answer usually proposed by soft path advocates, namely, that the playing field is not level for the competition between conservation technologies and supply-expanding technologies because of tax and other subsidies available to such industries as oil exploration. Another may be that energy, and economic growth as traditionally defined, remain a solution to many problems. As an example, Ausubel points out that catalytic converters reduce the energy efficiency of cars, although they serve other highly desirable environmental objectives.

At a deeper level the problem may be that end-use efficiency is almost always the result of a process involving several links in a chain. Ayres points out that a new process that saves one link in the chain between raw materials and final goods or services can usually be justified in terms of savings in raw materials, energy, or capital requirements. Final products are made by sequences of processes with an overall conversion efficiency that is the product of the efficiency at each stage. If a typical chain has four steps, each with a very favorable conversion efficiency of 0.7, the overall conversion ratio of the chain (i.e., 0.7^4) is about 0.24. The world energy system appears now to have an overall efficiency of only about 0.15. We have been climbing the overall efficiency curve steadily but slowly, on average about 2 percent per year over the past 100 years, a rate requiring 35 years for a doubling of performance (Grübler and Nakicenovic, 1989). The promise of energy efficiency is there, but the basic structural problem may yield only gradually. Meanwhile, it makes sense to seek gains at each link in the chain and to pursue efficiency technologies that would both moderate demand and deliver supply more cost-effectively. The latter would include research into such areas as superconducting cables for electricity transmission, magnetic induction for motors and transportation, and microwave heating.

As Friedlander points out, there should be a large, profitable market for technologies that are both environmentally and economically competitive. Inherently safer and less-polluting plants should cost less for several reasons. Presumably, prevention of pollution should pay for itself through reduced demand for inputs and reduction in waste disposal and liability costs. Moreover, if products can be made smaller and lighter without loss of quality, there may be an economically attractive reduction in space required for manufacturing and storage and in transportation costs.

A critical question is on what terms wealthier countries will transfer low-pollution technologies to developing countries. Friedlander points out several consequences of worldwide increases in pollutant emissions that will occur as more nations industrialize:

- pressure for further regulation at the international level,

- difficult international negotiations aimed at setting national emission allocations, and
- competitive advantage to nations whose engineers are able to design clean, economic technologies.

We may be entering a new era of complex global bargaining, where environmental quality is a major objective and where environmentally attractive technologies and resources are major bargaining chips. What terms will be required to prevent the cutting down of tropical forests or the building of new coal-burning power plants? Environmental protection on a global scale will require the nations with low-pollution technologies to transfer these in a timely fashion in both subsidized and unsubsidized ways.

The research agenda must recognize that we face complex, interdisciplinary problems, that systems research is required, that we should acquire as much information as possible at a minimum within reasonable cost boundaries, that we should address these with operational and social science as well as engineering and natural sciences, and that many points of view should be folded in. We should strive to go from particular problems toward general analytic understanding and global methods. The lack of training in methods for solving complex problems is evident in the history of environmental policy, as Tschinkel illustrates.

Yet, the partial nature of solutions must be accepted. On most environmental issues, the luxury of time to search for optimality does not exist, as Glas's account of the ozone controversy demonstrates. In many areas, decisions are being made in real time or on the basis of anticipated consequences. However, a sequence of partial solutions may form a good path if the forces driving the system are reasonably well understood. The key is to work on narrow or specific problems with an understanding of the interface with the overall problem; this is well illustrated by questions surrounding clean coal technologies (which could alleviate acid rain) and CFC substitutes (which might not destroy ozone) but could intensify concerns about greenhouse warming. Isolating meaningful subsystems is not always easy, especially in turbulent, dynamic systems such as those in which most environmental issues exist. Still, it is necessary to take the long and dynamic view and to build the research capital and data base. Moreover, as Ausubel points out, there may occasionally be simple and important relations to be found in complex systems. The challenge is to couple technological, economic, and environmental considerations without unrealistic data needs and analytic paralysis that can come with overly ambitious modeling efforts.

CONCLUDING THOUGHTS

Some of the toughest issues facing us—urban air pollution, climatic change, destruction of rain forests, and loss of habitat, for example—are the consequences of large-scale cultural patterns, the summed effects of millions of people making individual decisions. Engineering communities have become painfully aware that such phrases as the "tragedy of the commons" and the "tyranny of small decisions," described by Lynn, are accurate descriptions of reality, a reality that is most difficult to alter. What will be needed to make more people work together and act for the common good? Gray suggests that we are caught in a gridlock of adversarial relations on environmental matters, but only when virtually everyone wants to escape can such social traps be broken.

Certainly there is a need to educate individuals about how behavior in exercising consumer preferences affects local and global environments. In the environmental problem in the large, we confront the desire for a generalized freedom; as individuals, we do not want constraints imposed that affect mobility, life-style, convenience, or purchasing decisions. To quote Lynn, "It is true that regulations reduce our freedom of choice, but so does a deteriorating environment." Tschinkel's formula for progress is to have a sound scientific base and incentives for doing the right thing and to engage people for cooperation early in the process, to recognize that human beings are mere mortals, to be relatively site specific and results oriented, and to seek agreements that are negotiated and approved by all parties.

As Ayres points out, contrary to popular belief, long-term goal orientation in economic life is not particularly rare. But there is a need to increase shared recognition of a long-run evolutionary imperative that favors an industrial metabolism that results in reduced extraction of virgin materials, reduced loss of waste materials, and increased recycling of useful materials. Although the overall trend may not yet exist, the imperative is to seek reduced materials intensiveness or dematerialization.

Technology should become a ground on which takes place the problem-oriented reintegration of the domains of human knowledge and social development. As Tschinkel reminds us, customary scientific analysis does not show what is detrimental for the environment and what is not; it states what consequences logically follow from what activities. Accelerated by new research programs, natural science will very likely reveal more in the 1990s about nature than mankind has ever known, but scientific analysis as traditionally practiced will remain unseeing with respect to human needs. Meanwhile, the social sciences, especially economics, which in theory address human needs, have proved almost blind with regard to nature. The intersection of technology and environment in a sense has been the blind spot in our system of knowledge, and this gap is at the root of today's environmental crisis (Meyer-Abich, 1979).

Environmental engineering, recognizing our own nature as part of nature and our technology as in nature, can help bridge the dangerous compartmentalization of knowledge and professions that appears to be placing modern life in jeopardy. The technological potential is there for both economic growth and improvement in environmental quality. However, technological and scientific development is embedded from the beginning in social developments, and there we must harmonize incentives to foster a world of environmental and economic quality rather than desolation and self-burial.

We must also accept that in responding to many environmental questions, we may never know whether we are right or wrong even in the case of more narrowly defined scientific aspects of a given issue. Much of the environmental investment that must be made in coming decades will be like the building of the great Gothic cathedrals, performed out of respect for large and durable forces and to address noneconomic concerns. We cannot be certain what would occur if we fail to take precautions. Many of the challenges to be faced, like global warming, exist to a considerable extent in the domain of "hypotheticality" (Häfele, 1975).

So then what will be the verdict on the earth transformed by human activity? We should not simply stand by to find out, but try always to create the technological conditions in which it will be meaningful and satisfying to ask many other questions about human existence.

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