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SUCCESS, STRAIN, AND SURPRISE

Robert W. Kates

PROLOGUE: *In the past 15 years there has been a marked shift in the nature of the hazards that concern both citizens and public officials. Visible problems of air and water pollution have given way to greater emphasis on the less-visible problems of toxic chemicals whose consequences are not well understood. This change has placed a heavy burden on regulatory agencies that attempt to assess and manage hazardous new technologies and the scientists who advise those agencies.*

Changes are also taking place in hazard management outside of government as both public interest groups and industrial managers search for alternatives to governmental regulation. Greater skill in managing hazards unfortunately has not altered the fact that both scientists and the public continue to be surprised by new hazards that are the inevitable by-product of technological change.

In this introductory article geographer Robert W. Kates discusses the barriers to further progress imposed by the limits of our scientific knowledge, the shortcomings of the institutions responsible for regulating hazards and compensating victims, and the difficulties in providing equity when managing technologies present varying risks and benefits for different segments of society. He describes the search for technological and behavioral fixes that can help overcome these barriers and warns that future changes in the use of technology will present new hazard problems, as well as new opportunities for hazard reduction.[1]

Robert W. Kates received his Ph.D. in geography from the University of Chicago in 1962 and has been on the faculty of Clark University ever since, currently as professor of geography and research professor in the Center for Technology Environment and Development. His current research includes the management of technological hazards, the impacts of climate variation, and theories of the human environment. He is the editor (with Jesse Ausubel and Mimi Berberian) of Climate Impact Assessment: Studies of the Interaction of Climate and Society *(1985). He is also the editor (with Christoph Hohenemser and Jeanne X. Kasperson) of* Perilous Progress: Managing the Hazards of Technology *(in press).*

In the past decade and a half, citizens of most industrialized countries have become concerned about the hazards of technology, have created a new set of institutions and activities to control them, and have profoundly changed the ways in which technologies are designed, produced, and used. Over the next decade and a half, more subtle hazards will confront us, strains and contradictions will emerge in the new institutions, and we will still be surprised at the strange ways in which our technologies unintentionally injure us.

Fifteen years after Earth Day 1970, much progress has been made in the United States in controlling air and water pollution, somewhat more with the former than the latter.[2] At the same time, the hazards that we cope with today have changed markedly. There has been a shift in emphasis from visible problems of automobile smog and raw sewage to less-visible problems posed by low concentrations of toxic pollutants.[3] We are less concerned with the acute consequences of a hazardous technology such as the automobile (which are measured well by the National Safety Council) than we are with the chronic consequences of a hazardous technology such as toxic chemicals (which are not measured well) because either we do not understand the causation or the effects are still latent. Our concerns have shifted in temporal scale as well. We are less worried about the daily recurrence of commonplace accidents than about confronting the frightening possibility of rare but catastrophic accidents. And in spatial scale we are shifting attention from the local to the regional and global—from local improvement in water or air quality, achieved in almost every industrialized country, to regional frustration in dealing with acid rain, stratospheric ozone depletion, and tropospheric ozone enrichment, and to global uncertainty about carbon dioxide, trace gas enrichment, and nuclear winter.

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This shift from better-understood hazards to less-understood hazards has placed an enormous burden on science to identify hazards and to assess their risks. Scientists often fluctuate between humility and hubris, and scientific risk assessment has manifested these fluctuations as well. Currently, humility appears to be in ascendence as the limits to knowledge emerge and experts routinely contradict each other in the press or the courtroom. But it should be equally recognized that while the media, the public, or the courts may demand more of science than it can give, some scientists have promised more than they can deliver. Scientists have implied that they know the significant ways in which technologies fail, that they are close to understanding the fundamental causes of cancer and arteriosclerosis, and that hazardous waste can be safely collected, transported, and stored. Thus, while some scientists would limit the burden on science, others continue to extend it, either from hubris, from a desire to reassure the public, or because they relish the challenge and opportunities for further research.

II

As we shift our focus to more elusive hazards, the institutions of hazard management become more concrete. The institutionalization of government regulation is well known. New technological hazards that are wholly unregulated are rare. Indeed, recently perceived hazards, such as those of genetic engineering, come under regulation by at least five government agencies. Despite occasional resistance based on ideological reflex, the principle that hazards should be regulated is not seriously disputed. It is the wisdom, magnitude, social cost, and implementation of the specific regulations that fuel controversy.

The excessive focus on public regulation has obscured the institutionalization of hazard management that has taken place outside of government. For example, groups claiming to represent the public interest consistently monitor most domains of hazard. Often underfunded, such public-interest groups have nevertheless established legal and scientific competence that enables them to participate actively in public regulatory processes and to use the courts to guarantee implementation of congressional intent or to obtain compensation for injury. As these groups become more professional, they increasingly join with their counterparts in industry in efforts to implement regulations and to provide alternatives to regulation through voluntary efforts, environmental mediation, and the like.

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Another set of hazard management institutions are judicial ones arising from the remarkable innovation of contingency representation in class-action compensation and liability cases. This institutionalization of representation follows a long-term shift in both public attitude and legal precedent, from concern with acts of God to acts of persons and from private risk to public risk. Where a resigned public once hesitated to sue a steamship company for injury from a boiler explosion, an indignant public now blames the government for causing floods. In a time when lawyers routinely advertise for clients, insurance and self-insurance reserves provided for hazard compensation are being seriously strained.

But the most remarkable institutional change—and one receiving the least formal study—has occurred within industry itself. For the last two years I have been part of a modest research effort seeking to learn more about how corporations manage hazards.[4] Our studies are limited; the corporate world appears reluctant to allow external inspection or to encourage internal self-examination. But even our limited studies suggest a remarkable set of changes over the last 15 years in corporate goals and in resources devoted to the management of hazardous technologies.

Since 1970, when General Motors established its public policy committee, U.S. industry has institutionalized the social responsibility movement, creating codes of ethics in many corporations and board of directors' committees in some of them, and, most important, establishing specific policies and operational guidelines in major corporations, such as Dow, Du Pont, and Monsanto, that produce hazardous products. Common elements in these operational guidelines include intensive efforts to screen for potential toxicity; attention to worker health and safety; concern that consumers are protected and that company products are used safely; protection of the environment by waste reduction, pollution control, effluent cleanup and safe waste disposal; and disclosure and dissemination of correct product information.

Industry has also committed resources. A recent Chemical Manufacturers Association survey in which about half the industry responded found that the mean firm surveyed had 84 health and environment specialists, or about 2 percent of its U.S. employees, and spent almost 4 percent of annual sales on toxicity testing and environmental pollution control.[5] One industry leader that our group studied had a 125-employee headquarters health and safety unit, including an epidemiologist and a risk-assessment unit, a toxicology lab with 20 toxicologists, and 30 industrial hygienists assigned to plants—resources probably exceeding those of most state governments.

The resources of an industry leader may be misleading. Our limited studies have focused on large and prosperous corporations, and even within this set there are large variations in commitment and resources. Nonetheless, the major changes in approach and staffing since 1970 are widespread. Indeed, we have found that a corporate health and safety regulatory system exists that matches that of the public sector. This shadow government employs a variety of standards. Generally, these include the relatively few standards that are mandated by government, the many more industry consensus standards, and some internal corporate standards developed for new products and facilities or to maintain a higher standard of workplace health and safety. This standard-setting process is replete with many of the conflicting roles and motivations found in the public process, and in some corporations it is based on an extremely sophisticated risk-assessment process. As with the governmental process, it is easier to set standards than to enforce them. But a genuinely committed firm may be able to enforce its own standards more easily than the government can regulate that firm.

III

Underlying the institutionalization of hazard management is a vital change in public attitudes. In the late 1960s three powerful movements—those concerned with the environment, consumerism, and, more recently, personal health—began to overlap and coalesce. The strongest of the three, the environmental, is founded on deeply held values and strong, persistent attitudes. Polls have consistently shown that concern with air and water pollution, support for strong government regulation, and sympathy for the environmental movement claim favor with two-thirds of the population despite liberal-conservative political affiliations and fluctuations.[6] The more recent and somewhat amorphous personal health movement can only reinforce these concerns about hazards.

Although techniques and institutions vary, a commitment to the management of technological hazards is deeply entrenched in most industrialized countries. The costs are substantial. Modern industrialized countries commonly devote between 1 percent and 2 percent of their gross national product (GNP) just to prevent and reduce pollution. Our study group calculated that in 1979 the social cost of coping with hazards associated with technology in the United States was equivalent to between 7 and 12 percent of GNP, with about half devoted to hazard management and the remainder incurred as damages to people, material, and the environment.[7] These expenditures reflect the stable commitment to environmental values forged over the last two decades and its implementation in major political and economic institutions. Coping with the emergent issues of the next 15 years begins on that base, and the maturation of nonfederal institutions offers new opportunities.

One goal of professional risk and hazard assessment is to minimize surprise. Notwithstanding the substantial resources now devoted to the management of technological hazards, one of the distinguishing features of the last 15 years is that surprise persists and, paradoxically, grows.

While the partial core meltdown at the Three Mile Island nuclear plant on March 28, 1979, was within the range of uncertainty postulated by some assessors of the risk of nuclear accidents, the public and most scientists were surprised by the event. Other examples of major surprises include acquired immune deficiency syndrome (AIDS), the Bhopal disaster, Legionnaires' disease, natural carcinogens, the nuclear winter scenario, suicide truck bombs, toxic shock syndrome, and poisoned Tylenol. Hazardous surprises seem to occur at a frequency of about twice a year worldwide.

Paradoxically, success in managing hazards fuels our surprise. The conquest of many common infectious diseases makes the outbreak of new infectious diseases surprising, not only because of the complexity of the pathogens involved but also because of the mix of social behavior and technologies involved in their transmission: conventions, homosexuality, blood-distribution networks, superabsorbent tampons, and air-conditioning systems. The remarkable record of purity in our food and drugs heightens the impact of a mass poisoner. Our vaunted military strength makes our vulnerability to the truck bomber seem astonishing.

But there are also genuine scientific surprises. Forty years after Hiroshima, nuclear winter, a major new consequence of nuclear war, is hypothesized.[8] Long after the identification of natural carcinogens such as aflatoxins in peanut butter, we are still surprised by their extent and potential toxicity.[9]

Surprising hazards are an inevitable outgrowth of technological change. One of the positive developments of the past 15 years has been the growing public understanding that all technology is hazardous and that some technologies are substantially more hazardous than others. I believe that the demand for totally safe technologies has diminished. Technological innovation will surely produce new hazards, and many of these will prove quite surprising despite the successful institutionalization of the processes of ensuring early hazard identification and product safety.

Identifying potentially hazardous technologies may become more difficult because of a troubling characteristic of the so-called high technologies. Since 1939 three major high technologies have dominated the innovation process: nuclear engineering, solid state electronics, and biotechnology. A characteristic of the development of these technologies has been the blurring of the roles of the basic scientist, the technologist, and the entrepreneur—a blurring hailed by many as leading to quicker innovation, application, and use. This pattern began with the atomic bomb, when Albert Einstein wrote to President Roosevelt about the military implications of atomic energy and a generation of physicists worked as technologists to make it a reality. It is most evident today in the development of biotechnology, in which leading scientists assume all three roles. What is troubling is that this blurring of roles denies to hazard management one of its strongest sources of early hazard identification—knowledgeable but independent basic scientists. Such scientists, knowledgeable about a technology but independent of its development or production, are society's best bulwark against technological surprise.

Finally, it appears that it is intrinsically more difficult to predict the hazardous nature of some technologies than others. Scientific theories of comparative degrees of hazard are just being developed. My own research group recognizes five distinguishing characteristics of extremely hazardous technologies: intentional design as biocides (chemical pesticides); the combination of latency and long potency in materials (asbestos); the potential for catastrophic effects (jumbo jets); the persistent, ubiquitous capacity to inflict harm (motor vehicles); and the as yet unquantified capacity to cause damage of global extent (acid rain).[10] But high hazardousness is not necessarily surprising. Rather, the surprise or unpredictability of some hazardous technologies may lie in the qualities Charles Perrow identifies as high hazard—the combination of technological complexity, the tight coupling of components so that the failure of one component starts a process that cannot be arrested, and catastrophic potential.[11] Or the surprise may reside in the complex dynamics of biological and technological systems which C.S. Holling and his colleagues have studied, and in which there is great potential for serious, unwanted, and hazardous surprises (for example, in the interaction between pesticides and pesticide-resistant insects).[12]

IV

The capability and competence of the hazard-management system that has evolved in recent years is substantially limited.

The capability and competence of the hazard-management system that has evolved in recent years is substantially limited. Without major breakthroughs in our fundamental understanding of the mechanisms of low-level effects of toxic chemicals and radiation, for example, there are clear limits to our ability to quantify these effects. Similarly limited is our ability to anticipate and prevent catastrophic accidents. And society as a whole cannot reduce *all* hazards or reduce *any* hazard to zero risk.

A second set of limits is institutional. Ten or more years after most regulatory agencies were created, considerable doubt remains whether they can carry out their legislative mandate to set standards and to force compliance with them. Federal air pollution standards exist for only a few of the hundreds of known airborne toxic substances. There are even greater doubts as to the judicial system's capacity to deter negligence and to compensate efficiently and justly for injury. Insurance companies and other risk-sharing institutions linked to that judicial system appear to be in crisis, overwhelmed by the legacies of old hazards such as asbestos, changing concepts of responsibility, and the potential for future Bhopal-like catastrophes. Finally, our exemplary tradition of voluntary action, public-interest initiative, and corporate good citizenship seems inadequate in the face of such overwhelming tasks as the cleanup of thousands of existing hazardous waste sites.

A third set of limits relates to moral choice—the perennial conflict between efficiency and equity. Hazards pose special and subtle problems. These include the separation in space and time of those who receive the benefits of technologies from those who experience the risks; the wide differences in hazard susceptibility between individuals, ages, sexes, and even ethnic groups; and the uncertainty as to both cause and responsibility when compensating for injuries inflicted by substances such as asbestos or Agent Orange.

These limits are hardly absolute; their boundaries still need to be explored. Some believe that the effectiveness of the hazard-management system, recently created in this country and still in flux, has yet to be thoroughly tested. Nonetheless, an interesting search for alternatives is already under way. It includes a search for ways to finesse the uncertainty imposed by the limits to our scientific knowledge, to diminish the catastrophic potential of technology, and to choose an agenda of hazards that pose the greatest threat to our society. It seeks alternatives to government regulation and litigation and new ways to link equity and efficiency in compensating victims of hazards. It is a search for technological and behavioral fixes.

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V

I served my apprenticeship in hazard science 25 years ago at the University of Chicago under the leadership of Gilbert F. White, whose work involved analyzing the failure of the major engineering works that had been used since 1936 to reduce riverine flood hazard in the United States.[13] As engineering projects they worked well, but as social engineering efforts they had a perverse effect. While they reduced the frequency and magnitude of flooding, they also encouraged the development of floodplains. Thus, there were fewer floods but greater damages. A behavioral fix was needed to complement the prevailing technological fix, and we sought to develop one with a broad program of management innovations in the form of scientific information, floodplain regulation, insurance, emergency evacuation, and incentives for floodproofing individual buildings. I started my career, therefore, skeptical of technological fixes and with a bias toward behavioral fixes.

Like the engineering projects that reduce the numbers of floods while amplifying potentially catastrophic floodplain development, there are similar perverse combinations of factors found in many hazard-management situations. For example, students taking driver training courses in high school have somewhat safer driving records than untrained ones. However, because the institution of such courses has been accompanied by a widespread lowering of the age of licensing, the number of young drivers, as well as their overall accident toll has increased.[14]

Confidence in single fixes—technological or behavioral—is usually misplaced. The projected diminution in risk or consequences from the single fix is often overestimated, partly because of the energetic advocacy of its proponents. More often, however, the single fix overlooks some process elsewhere in the chain of causation that either increases the releases, exposures, or consequences of the hazard or introduces a new chain of hazard. Thus, even the most successful of recent simple technological fixes, the childproof drug container that has substantially reduced child-related deaths, creates painful frustration for elderly arthritics and annoyance for all of us. On the other hand, well-managed hazards, exemplified by commercial aviation, employ a spectrum of fixes at every stage in the chain of hazard causation. They combine both behavioral and technological fixes—better crew training and better aircraft. In what follows, I suggest some alternative fixes for coping with technological hazards, but with the warning that although they could be useful, they are not universally applicable.

VI

One desirable class of technological fixes—inherently safe processes—depends on immutable laws of nature rather than the intervention of humans or electromechanical devices.[15] Two such systems have been proposed for nuclear reactors, and suggestions for somewhat similar processes are available in chemical engineering. Inherently safe waste disposal is also possible where pretreatment, high-temperature incineration, or constant recycling reduce the toxicity of waste by many orders of magnitude. It now seems clear that efficient hazard reduction poses as great an engineering challenge as efficient product production.

I would also offer a second class of technological fixes—the inherently simple fix. I have cited one example, the childproof drug container. Related to it are the post-Tylenol sealed containers. Innovations in chain-saw safety following the epidemic of accidents that resulted from greater use of firewood during the recent energy crisis are another example. Inherently simple fixes require a well-understood hazard, some motivation to cope with it, and a bit of old-fashioned ingenuity.

Now that government has attempted to regulate almost every hazard, it is clear that there are real limits to regulation. These limits stem from ideological distaste for government regulation and, more pragmatically, from the inherent shortcomings of rulemaking processes and compliance efforts. These limits suggest a need for behavioral fixes—changes in human behavior—using the recently created resources of industry and public-interest groups in hazard prevention and reduction.

Theoretically, the hazard makers should be the best hazard managers. If they can be persuaded to do so, those who design and manufacture products are in the best position to identify potential hazards and to correct or control them. Much of the persuasion has been accomplished already. Controversy over the grim legacies of the past or the safety of existing products has obscured the real progress made in the design of new, less-hazardous products. Novel reporting requirements, such as the so-called squeal law provisions of the Toxic Substance Control Act (requiring manufacturers to report any knowledge of substantial risks), attempt to use industry's own considerable scientific resources. Many more voluntary and creative experiments using industry, public-interest groups, and the scientific community are needed.

Let me illustrate one such possible effort. Recently, the Board on Toxicology of the National Research Council (NRC) completed a shocking study on available toxicity data.[16] Based on a sample of some 53,500 distinct chemical entities, the board found that minimal toxicity information was available for only a third of the drugs and pesticides, a quarter of the cosmetics, and a fifth of the chemicals in commerce. In contrast to the virtues of the de minimis approach that proposes to ignore very low levels of hazard, our society seems to have adopted a de ignoramis approach that avoids knowing about many hazards.

Industry may well quibble with the standards of minimal knowledge that require new chemical compounds to be tested for toxicity by rodent studies that are expensive and time consuming. But the NRC study employed and, for the most part, was limited to publicly available data. Industry conducts an extraordinary amount of proprietary testing of new chemical products, the results of which may be withheld if the corporation does not develop the product further. Corporate executives are reluctant to disclose these data because screening tests are a significant business expense and they do not wish to reveal to competitors their search strategy for new chemicals. Given the cooperation of industry, it should be possible for an independent scientific body, such as the NRC, to review these test data confidentially and prepare a composite list of mutagenic chemicals to be issued annually, with the proprietary sources held in confidence.

The final form of the procedure is not important, but the principle is. As a society we need to use our collective hazard-management resources in ways that avoid the ponderousness of the regulatory system and the competitiveness of the marketplace.

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Similarly, we need some new behavioral fixes in our procedures for compensating the victims of hazards. Compensation itself is a failure of hazard management, usually inadequate to match the loss, pain, and suffering incurred. Our current system is in crisis and extremely costly. Insurance premiums continue to rise; some malpractice insurance costs are prohibitive; and corporate failures, including those of major liability insurance companies, are likely. As physicians and the producers of vaccines can attest, malpractice and product-liability suits threaten both innovation and useful institutions. But worst of all, the system with all its high costs provides neither compensation nor fairness to large numbers of victims.

A vigorous national search is on for alternatives, including no-fault environmental compensation programs or caps on liability. This search has been encouraged in part by widespread reaction to pictures of liability lawyers descending on Bhopal in search of clients. As the tragedy of Bhopal slowly wends its way through the U.S. court system, it may be instructive to examine a different way of handling an industrial tragedy—the response of the Mexican government to the natural gas explosion on November 19, 1984, at San Juan Ixhuatepec.

The disaster killed at least 500 persons, injured over 2,500, and displaced 200,000 or more. It was marked by a restoration, reconstruction, and compensation process unmatched by responses to natural and technological disasters anywhere in the world. The response of the Mexican government, as chronicled by my colleague Kirsten Johnson, was remarkably prompt.[17] The delivery of rapid, albeit rough and ready, aid and compensation in the San Juan Ixhuatepec episode provides an example of an alternative to more traditional judicial processes that may be exceedingly fine but are also exceedingly slow.

In the beginning the relief effort was marred by the same misplaced generosity that characterizes many disasters—unwanted clothing and undistributed food. But within three days of the disaster, large quantities of building materials were delivered to the site to be given without charge to all residents with damaged property. This led to an immediate spate of self-help reconstruction and general neighborhood improvement. One section of the explosion site was made into an instant park, ostensibly to commemorate the victims, but also to preserve the area as a buffer to separate residential areas from land suitable for a future industrial site and to replace the scenes of the disaster with greenery and games. A health facility was put in place and a community center will follow, providing a minimal type of community compensation. To provide housing to about 200 displaced families, part of a newly completed housing development was acquired by the government, and before the week was out the first homeless families received permanent housing. Within another week 80 percent had been housed.

On Christmas Day five weeks later, the Mexican national oil corporation (PEMEX) denied liability but accepted responsibility for the disaster and pledged to pay compensation of more than $10,000 per death victim. There were no precedents for such payments, so the payment schedule was adapted from the workman's compensation code for the various classes of death and injury. Less than three months after the disaster, almost all the victims or their heirs were compensated.

Three months saw a community rebuilt, the homeless housed, and the victims compensated. The speed of the settlement came at the price of an authoritarian uniformity—all victims received the same housing. Some were better off than before, others were surely worse off and removed from their former community. Some nonvictims benefited from the free materials. An occupational compensation scheme was adapted for public use that in litigation might have provided higher settlements. And the park was placed on the destroyed living area and not on the industrial site as some residents expected, thereby forcing the permanent removal of the homeless. But for most victims and for the public at large, some justice was done.

A final example of a behavioral fix needed for the next decade lies in the development of third-generation ethics. The first generation of hazard-management ethics was the ethics of nonmaleficence—do no harm to person or nature. These ethics were celebrated on Earth Day 1970, enshrined in regulatory law, and finally institutionalized in corporate codes of ethics indistinguishable from those of the Audubon Society—all in the space of a little more than a decade.

The second generation of ethical issues attempted to weigh harms—to consider both benefits and the value of lost benefits as well as risk. The ethical underpinnings of this approach, an extension of cost-benefit analysis,were dominated by principles of utility.

Third-generation issues concern equity, fairness, and distributive justice. They are concerned not only with the overall balance of benefit and harm but with their distribution to specific groups or individuals, with the fairness of the process as well as the outcome. These issues are prominent in many situations. Trying to avoid the exposure of women of reproductive age to toxic chemicals poses complex questions of sex discrimination, invasion of privacy, and protection of the unborn, as well as of establishing permissible levels of exposure.[18] A pervasive and ethically unjustified double standard in the protection of workers and the public exists almost everywhere. The standards of workers' exposure to toxic materials are 10 to 1,000 times greater than those applied to the general public.[19] The Bhopal disaster illustrates still another double standard in safety performance, that of industrialized and developing countries.[20] Hazardous waste disposal practices concentrate wastes gathered over a large area in someone's backyard and pass on a legacy of care and risk to future generations.[21]

All of these are third-generation problems requiring ethical analysis capable of illuminating policy choices in modern hazard management. Thus, it is particularly troubling that the widely praised National Science Foundation Program on Ethical Values in Science and Technology (EVIST) may be abolished or dismembered even though the work done under its aegis—the development of a competence for ethical analysis and technological choice—promises to combine rigor and compassion.

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As we eschew the single fix, be it technological or behavioral, we should also avoid the choice of a single ethic. It is possible to create a process that addresses the different needs of groups at risk, leading not to a perfect resolution of ethical dilemmas, but to a fairer distribution of the risks and benefits of technology. Scientific and technological fixes can also help by reducing the overall risk or by identifying and protecting groups at greater risk.

VII

Two centuries after the beginning of the industrial-scientific revolution in the design, production, and use of technology, modern societies began the comprehensive management of the technological hazards created in its wake. Whether one dates the beginnings of this effort with the popular outcry of Earth Day 1970, as I have, or from the early warning of Rachel Carson's *Silent Spring* in 1962, or from the classic paper of Chauncey Starr in 1969[22] that started the professional development of comparative hazard management, the movement is less than a quarter of a century old. The real changes in the way society handles technological hazards are less than 15 years old. But so profound has been the shift in attitudes, institutions, and activities that, in retrospect, these changes may well be viewed as no less revolutionary than the technological revolution that preceded them.

Over the next 15 years the changes will be less profound but the problems may be no less important. I foresee four sets of concerns. The first I have discussed extensively—the limitations, strains, and contradictions of the first 15 years of activity and the search for alternatives to ease or resolve them.

Another set of concerns relates to the major changes under way in the design, production, and use of technology. New products will bring new hazards. Old products and processes in new locales will bring new hazard problems. The rapid restructuring of world industrial production will reduce the hazards in places that have learned to cope with them and move hazards to places where the knowledge and resources for control are not available. At the same time the potential for closed-cycle production, inherently clean or safe processes, and robotics will provide new opportunities for hazard reduction.

The new institutions and activities developed over the last 15 years to cope with hazards in our own country have proved inadequate so far to cope with the newer regional- and global-scale problems exemplified by the biogeochemical cycles of carbon, nitrogen, phosphorus, and sulfur—the basic elements of life. Research over the last 15 years has led to quantitative estimates of the degree of human modification of these natural cycles.[23] The annual release of carbon dioxide to the atmosphere from the consumption of fossil fuels equals about 10 percent of that being used by plants for photosynthesis. The formation of nitrogen oxides and nitrate in the course of fuel combustion and fertilizer manufacture equals about half of what the biosphere produces naturally. The amount of sulfur oxides released to the atmosphere, primarily from fossil fuel burning, exceeds the natural flux from decaying organic matter. These seem to be large alterations in natural cycles, but their long-term implications and synergistic interaction are uncertain. Over the next 15 years we will surely learn more about these fundamental processes, but our science is likely to exceed our social and political capacity to act upon such understanding.

Finally, there will be surprises—surprises that in turn will generate new concerns and activities. There will also be other concerns and surprises unrelated to technological hazards: international tensions, social change, and resource needs. As in the past, these will replace technological hazards on center stage, but the work in the wings will continue. The fundamental attitudinal and institutional changes of recent years have acquired a momentum of their own. The effort to compensate the past, make safe the present, and protect the future will continue. ■

NOTES:

1. This article was adapted from a paper delivered at a June 3–4, 1985, National Academy of Engineering symposium on "Hazards: Technology and Fairness." A report on that symposium will be published in book form by the National Academy Press. In preparing this article, I have drawn extensively from the collective research and insight of the Clark University Center for Technology, Environment, and Development Hazard Assessment Group and particularly Christoph Hohenemser, Kirsten Johnson, Jeanne X. Kasperson and Roger E. Kasperson, and Mary Melville. In addition, I have had the benefit of thoughtful comments from Jesse Ausubel, Meredith Golden, and Howard Kunreuther.
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