Proc. Natl. Acad. Sci. USA
Vol. 80, pp. 7027–7038, November 1983
Review

Comparative risk analysis of technological hazards (A Review)

(risk assessment/hazard management/uncertainty)

ROBERT W. KATES*† AND JEANNE X. KASPERSON†

*Graduate School of Geography and †Center for Technology, Environment, and Development (CENTED), Clark University, Worcester, MA 01610

Contributed by Robert W. Kates, June 20, 1983

ABSTRACT **Hazards are threats to people and what they value and risks are measures of hazards. Comparative analyses of the risks and hazards of technology can be dated to Starr's 1969 paper [Starr, C. (1969) *Science* 165, 1232–1238] but are rooted in recent trends in the evolution of technology, the identification of hazard, the perception of risk, and the activities of society. These trends have spawned an interdisciplinary quasi profession with new terminology, methodology, and literature. A review of 54 English-language monographs and book-length collections, published between 1970 and 1983, identified seven recurring themes: (*i*) overviews of the field of risk assessment, (*ii*) efforts to estimate and quantify risk, (*iii*) discussions of risk acceptability, (*iv*) perception, (*v*) analyses of regulation, (*vi*) case studies of specific technological hazards, and (*vii*) agenda for research. Within this field, science occupies a unique niche, for many technological hazards transcend the realm of ordinary experience and require expert study. Scientists can make unique contributions to each area of hazard management but their primary contribution is the practice of basic science. Beyond that, science needs to further risk assessment by understanding the more subtle processes of hazard creation and by establishing conventions for estimating risk and for presenting and handling uncertainty. Scientists can enlighten the discussion of tolerable risk by setting risks into comparative contexts, by studying the process of evaluation, and by participating as knowledgeable individuals, but they cannot decide the issue. Science can inform the hazard management process by broadening the range of alternative control actions and modes of implementation and by devising methods to evaluate their effectiveness.**

> Living with technology is like climbing a mountain along a knife edge which narrows as it nears the summit. With each step we mount higher, but the precipices on either side are steeper, and the valley floor farther below. As long as we can keep our footing, we approach our goal, but the risks of a misstep constantly mount. Furthermore, we cannot simply back up, or even cease to move forward. We are irrevocably committed to the peak (ref. 1, pp. 34–35).

Thus Harvey Brooks encapsulates an ambivalence that has come to characterize both scientific and popular attitudes toward technology. Such ambivalence may well mark a watershed that separates our age from centuries of equating technology with progress. In an increasingly technological society, the notion of progress persists, but now it runs up against a heightened perception of technology as hazard.

Enter the risk assessors and hazard managers. Self-appointed or summoned by society, they come from diverse disciplines and professions (Table 1) to anticipate, identify, estimate, evaluate, and manage the myriad threats attendant on technologies old, new, potential, and imminent. Their activity has spawned an interdisciplinary quasi profession, replete with its own terminology, methodology, and literature. The present paper examines a significant component of this fledgling field—the comparative analysis of risk and hazard. The review, which draws largely on a survey of 54 monographs and book-length collections published between 1970 and 1983 (2–55), concludes with suggestions of the ways in which science can enlighten the study and inform the management of technological hazards. First, however, comes a setting of the social and research contexts in which technology has taken on its dual nature.

Trends

The view of technology as hazard is scarcely unique to our time. Agricola in 1556 bemoaned the environmental toll taken by European mining operations (56). The novels of Dickens and Zola graphically depict the horrors of the Industrial Revolution. By the end of the 19th century a new science—demography—had emerged to record deaths and injuries. On the whole, however, the promise of technology held sway over its less savory aspects.

Current ambivalence toward technology is a much more recent phenomenon influenced in part by four trends in the evolution, perception, and management of hazard. Each trend embodies a kind of change: the first in technology itself; the second in the identification of hazard; the third in the perceptions, attitudes, and concomitant expectations and demands of people; and the fourth in the character of societal response to technological hazards.

Beginning with World War II and the development of the atomic bomb, an impressive technological revolution that has accompanied major expansion of certain goods and services has generated an alarming array of hazardous materials, products, and processes. These developments stem in part from the exponential increase in production of synthetic chemicals, the concentration by mining and processing of materials normally dispersed in nature, and the changes in energy flow and mineral cycling that accompany massive engineering works, transportation routes, and waste creation and disposal.

Commoner (57) has argued that these changes are fundamental and disjunctive, not simply a continuation of the processes initiated by the Industrial Revolution. In any case, improved monitoring has surely heightened the sense of technology as hazard. Major advances in analytic and bioassay methods virtually ensure positive identification of chemical and biological hazards (58, 59). New screening devices, computer models, and monitoring and surveillance systems enhance capability for identifying, estimating, and assessing hazards (49).

Recognition (or even mere suspicion) of new hazards also stems in no small measure from a discernibly heightened public perception of danger and from increased expectations and demands for protection and safety. Though trailing both hazard making and monitoring, public attitudes changed rapidly in the early 1970s and now show signs of leveling off as a continuing, potent force in the society. The environmental and consumer movements have lessened in intensity since the early 1970s, but that is more likely a measure of success in institutionalizing public protection than a diminution of public concern (60). In-

Table 1. Professions and disciplines engaged in research on risk and decision making

1. Toxicologists devise laboratory experiments to identify potential carcinogens, mutagens, and other toxic substances
2. Climatologists build models to predict the effects of atmospheric CO_2 concentrations on global weather patterns
3. Epidemiologists use large data bases to isolate statistical associations between various risk factors (e.g., pollution and diet) and various indices of morbidity and mortality
4. Physicists, chemists, and biologists study fundamental physical processes to facilitate the identification and assessment of risks
5. Ecologists investigate the tensions between the needs of humans and the needs of other organisms in an ecosystem
6. Economists explore the effects of regulation on inflation, employment, innovation, competition, and productivity
7. Legal scholars assess how various liability doctrines affect both the compensation of victims and the incentives for injurors to engage in risk-generating conduct
8. Psychologists develop and test theories about how people form perceptions about risks and about how people make personal decisions about risks in their daily lives
9. Communication specialists examine the potential effects of educational media campaigns on self-hazardous life-styles
10. Market researchers assess the consequences of advertising on the consumption of hazardous products and substances
11. Sociologists study the influences of peer pressure on teenage smoking and drinking habits
12. Political scientists describe and evaluate how different political and economic systems generate and cope with risks
13. Philosophers and political theorists study the value trade-offs and ethical considerations in risk and decision making
14. Demographers and biostatisticians compile and analyze risk indices to identify crucial trends in risks over time
15. Defense analysts weigh the deterrent effects of weapon systems against the risks of escalation in armed conflict
16. Classical and Bayesian statisticians study how inferences about uncertainties should be made, how new information about risks should be incorporated into old beliefs, and how information about risks from disparate sources should be combined in a formal decision analysis
17. Organizational theorists study how the incentives and rewards faced by employees in business firms and public agencies cause people to generate and cope with risks
18. Engineers design safer consumer products and cleaner production processes and worry about the cost and complexity of safety devices versus the risks of accidents
19. Geographers study techniques for managing natural hazards and natural disasters
20. Decision and management scientists develop methods for formalizing value trade-offs in decisions about risks

Data are from ref. 2, pp. 47–49.

deed, even in the face of grave economic recession and a national antiregulatory climate, recent polls demonstrate convincingly both a persistence of strong public values for environmental quality (61, 62) and a mounting concern over technological risk (61, 63).

The explanation for these perceptions, concerns, and expectations is elusive. Actual and identified increases in hazardousness may explain some of the shift, but other factors undoubtedly play a part. A recent report (2) points to intensified media coverage, the erosion of public confidence in risk-management (and other) institutions, and the perceived impotence attendant on a complex technological society. Real gains in the extension of life, the control of infectious diseases, the elimination of hunger, and the mitigation of insecurity from unemployment and old age have produced an affluent society that can better afford to concern itself with risk (40). Thus it is only now, with more pressing needs resolved, that society can train its worry on less apparent hazards such as radiation and chemicals. Or perhaps we may yet discover that changing public perceptions correlate with broad sweeps and episodic fluctuations in moods of societal optimism or despair, in periods of economic prosperity or decline, in desires for risk or security, or in the politics of liberalism and conservatism.

Societal response parallels trends of increased hazards and their public perception. In 22 years (1957–1978), the United States Congress enacted more than 178 laws dealing with technological hazards (B. Johnson, personal communication), generating an awesome legislative/regulatory domain, the full extent of which is just now beginning to manifest itself (64). That domain includes enabling legislation for the Environmental Protection Agency (EPA), Occupational Safety and Health Administration (OSHA), and Consumer Product Safety Commission (CPSC), three of four [the Food and Drug Administration (FDA) had existed for decades] major guardians of public health and safety. Paralleling the efforts of the legislative and executive branches, the courts render decisions on benzene (65), on the psychological impact of the accident at Three Mile Island (66), and on air bags (67), and prominent spokesmen fret over judicial authority and competence in the determination of tolerable risk (68, 69). Meanwhile the media, their capabilities enhanced by recruitment of staff with scientific backgrounds, report the fate of proposed legislation, the court decisions, and the carcinogen of the week.

It is important to bear in mind the recent vintage of these changes in technology, hazardousness, perception, and response. The staggering proliferation of technologies is at most four decades old, and the welling of public concern and the concomitant legislative and regulatory effort span little more than a decade. The effort to prevent, reduce, and mitigate hazards has elicited a new applied discipline and profession concerned with the assessment and management of technological hazards. And with the assessors and managers has emerged a body of research.

Comparative research on managing technological hazards

Modern research on the management of technological hazards dates to the publication in 1969 of Starr's seminal paper relating social benefit and technological risk (70). One may well quibble about this dating (71). Specialized fields such as engineering, product safety, insurance, industrial hygiene, and occupational medicine had conducted various types of risk analyses long before 1969, and natural hazards management (72) had enjoyed two decades of interdisciplinary research addressing some of the same impacts later examined for technological risks. Yet a bibliography spanning the years 1935–1983 includes only 41 entries dated prior to 1969 (73). Moreover, Starr's publication in *Science*, the premier interdisciplinary journal, represents the first attempt to undertake explicitly the *comparative* analysis of technological hazards.

The paper spurred the National Academy of Engineering to convene a symposium in 1972 (4) and the Engineering Foundation to sponsor a workshop in 1975 (74). Meanwhile, the Scientific Committee on Problems of Environment (SCOPE) sponsored international seminars and workshops in diverse places ranging from Holcomb, Indiana, to Woods Hole, Massachusetts (16), to Tihany, Hungary (26).

On the heels of these colloquia came the publication of book-length overviews and texts on risk assessment (11, 15, 16) and a major casebook on technological shock (14). The National Academy of Sciences stoked the fires when its Committee on

Science and Public Policy commissioned Lowrance to take stock of the role of science and scientists in determining safety (11). A series of workshops (13) sponsored by the National Science Foundation (NSF) in 1977 and its subsequent establishment of a program on Technological Assessment and Risk Analysis (TARA) provided some of the impetus for new research endeavors. In response to TARA, the National Research Council (NRC) established its Committee on Risk and Decision Making, which has undertaken an overview of the research field (2). Also, NSF/TARA has encouraged and supported the new international Society for Risk Analysis (SRA), which publishes its own journal (*Risk Analysis*), a newsletter (*Risk Newsletter*), and the proceedings of its annual meetings (50).

Under the auspices of the NSF and the NRC, then, the field of comparative risk analysis has achieved a kind of legitimacy. Anyone who questions the staying power of this new quasi discipline has only to look at the exponential growth of the literature since the publication of Starr's paper in 1969. Risk assessments of specific hazards or technologies abound; the NRC itself publishes annually 50 risk-assessment reports (75).

Two recent literature surveys speak to a burgeoning research effort, particularly in recent years. A NSF bibliography on risk analysis and technological hazards comprises some 1,000 citations to books, reports, and journal articles published between 1935 and 1983 (73). Tapping an extensive library on technological hazards, the hazard assessment group at Clark University selected for analysis 54 major books published between 1970 and 1983 (unpublished data). Differences in scope aside, both compilations reveal similar trends in research output. As Table 2 indicates, each 5-year interval brings a striking increase, particularly in recent years. In terms of book-length publications, the 1980s have already eclipsed previous decades. The Clark survey of 54 titles includes only 16 books for the entire decade 1970–1979, but 38 have already appeared in the period 1980–1983 (May).

The 1980s, then, promise an inundation of book-length publications. The Clark University survey, albeit far from comprehensive, is broadly representative of the directions in the field of comparative risk analysis. Others may well find the list too long or too short and may wish to argue for exclusion or inclusion of this or that title, but such contentions do not detract from the utility of the survey in providing an overall impression of an unruly adolescent field. Seven recurring themes thread their ways into the 54 volumes. Table 3 lists the books in chronological order and summarizes the incidence of seven themes: (*i*) overviews of the field of risk assessment or some aspect thereof, (*ii*) efforts to estimate and quantify risk, (*iii*) discussions of risk acceptability or tolerability, (*iv*) risk perception, (*v*) analysis of regulation, (*vi*) case studies of specific technological hazards, and (*vii*) agenda for research.

Table 2. Publications on risk assessment

Publication date	NSF (73),* no. of citations	Clark University,† no. of books
1935–1959	5	—
1960–1964	9	—
1965–1969	34	—
1970–1974	166	4
1975–1979	428	12
1980–1983 (May)	359	38
Total	1,001	54

* Includes policy-oriented books, reports, and journal articles on technological hazards and risk assessment.

† Limited to major monographs or book-length collections of papers on comparative risk assessment.

Overviews. A hazard, in our parlance, is a threat to people and to what they value (property, environment, future generations, etc.) and a risk is a measure of hazard. Specifically, risks are measures of the likelihood of specific hazardous events leading to certain adverse consequences. Risk assessment comprises three distinct steps: (*i*) the *identification of hazards* likely to produce hazardous events, (*ii*) *estimation of the risks* of such events and their contingent consequences, and (*iii*) the *social evaluation* or weighting of the risk so derived (16). As is characteristic in a new field, nomenclature and concepts differ slightly from author to author (2, 11, 15, 16, 26).

Risk assessment is but a subset of societal activity for the management of hazard. One view of the entire process (Fig. 1) portrays the structure of technological hazards as a linked causal chain surrounded by four managerial activities—*hazard assessment, control analysis, strategy selection,* and *implementation and evaluation*. The first of these, hazard assessment, predominates in the emergent field of comparative analysis of risk and hazard. Indeed, 47% of the volumes surveyed include overviews of some aspect of risk (or hazard) assessment. Few volumes review hazard management as a whole.

Most of the overviews of risk assessment include critiques of conceptual and methodological shortcomings, but some studies seek to evaluate the social, economic, political, and cultural settings that may impinge on the practice of risk assessment. Thus Lagadec (46) sees the "challenge of major risk" as a global issue—a series of clashes between reason and democracy. Other researchers advocate international comparisons (20, 26, 76, 77). In contextual terms, the most extensive view is that of Douglas and Wildavsky (40), who regard the very selection of risks to be assessed as a basic cultural choice. Missing from most overviews is adequate attention to the first step, hazard identification, in assessing risk. Confident somehow that hazards will be identified in time, risk assessment concentrates on estimating, evaluating, and managing known hazards.

Estimating and Quantifying Risk. The precise estimation and quantification of risk is a major goal of risk assessment and receives the lion's share of attention in the literature. At least 38 (more than two-thirds) of the volumes surveyed include some discussion of risk estimation. One conference focused solely on the measurement of risk (28) and another conference (36) and a text (39) addressed quantitative methods for assessing risk.

Judgments on risk require reliable estimates and quantitative measures are the hallmark of science. Yet such estimates rely largely on extrapolation—extrapolation from past experience, from experiments (usually with animals), or from simulations (often with computer models). The particular applications of such methods all entail scientific uncertainty, the magnitude of which is variable, the handling of which is crucial, and the explicit expression of which often separates better from weaker studies.

In general, the degree of uncertainty bears an inverse relationship to the scientific understanding of the causal structure of a given hazard. For direct consequences of frequent, repetitive events with well-established causal relationships, it is possible to estimate with considerable accuracy individual or societal (or both) risks of mortality. Motor vehicle death rates in the United States, for example, have remained in the same range (18–28 deaths per 100,000 population) for more than half a century (78). For extensively studied effects such as ionizing radiation, widely accepted estimates of the cancer risk from low-level exposure [a lifetime exposure of 1 rad/yr (1 rad = 0.01 gray)] vary—by an order of magnitude or more—according to

Table 3. Major book-length publications on comparative risk assessment (1970–1983)

Year	Author(s) or editor(s)	Overview	Risk estimation	Acceptable risk	Perception	Regulation	Case studies	Research agenda
1970	Calabresi (3)					+		
1972	National Academy of Engineering/Committee on Public Engineering Policy (4)		+	+	+		+	+
1972	Sinclair *et al.* (5)		+	+	+		+	
1974	Epstein & Grundy (6)		+			+	+	
1975	Ashford (7)		+	+		+	+	
1975	Chicken (8)		+	+			+	
1975	NRC/Committee for the Working Conference (9)		+	+				+
1975	NRC/Committee on Principles (10)		+	+		+		+
1976	Lowrance (11)		+	+	+			
1977	Council for Science and Society (12)		+	+	+	+	+	+
1977	Kates (13)	+	+	+	+	+		+
1977	Lawless (14)					+	+	
1977	Rowe (15)	+	+	+	+			
1978	Kates (16)	+	+	+	+		+	
1979	Goodman & Rowe (17)	+		+	+	+	+	
1979	Hammond & Selikoff (18)		+	+		+		
1980	Conrad (19)	+	+	+	+			
1980	Dierkes *et al.* (20)	+		+	+	+	+	+
1980	Dowie & Lefrere (21)	+		+	+		+	
1980	Hovden (22)		+	+	+			+
1980	The Open University (23)	+	+	+	+			
1980	Salem *et al.* (24)		+	+	+			
1980	Schwing & Albers (25)		+	+	+		+	+
1980	Whyte & Burton (26)		+	+				+
1981	Baram (27)					+	+	
1981	Berg & Maillie (28)		+			+	+	
1981	Crandall & Lave (29)		+			+	+	
1981	Ferguson & LeVeen (30)		+			+		
1981	Griffiths (31)	+	+	+	+		+	
1981	Haimes (32)	+		+	+	+		
1981	Lave (33)		+	+		+	+	
1981	Nicholson (34)		+	+		+		+
1981	Richmond *et al.* (35)			+	+	+		
1981	The Royal Society (36)		+	+	+	+		
1981	Siddall (37)		+	+				
1982	Burton *et al.* (38)	+	+	+	+	+	+	
1982	Crouch & Wilson (39)	+	+	+	+	+	+	
1982	Douglas & Wildavsky (40)	+		+	+			+
1982	Fischhoff *et al.* (41)	+		+				+
1982	Hohenemser & Kasperson (42)	+	+	+	+	+	+	+
1982	Inhaber (43)		+				+	
1982	Kunreuther (44)	+	+	+	+			
1982	Kunreuther & Ley (45)	+			+		+	+
1982	Lagadec (46)	+		+		+	+	+
1982	Lave (47)	+	+			+	+	
1982	NRC/Committee on Risk and Decision Making (2)	+	+				+	+
1982	Poole (48)					+	+	
1982	Prentice & Whittemore (49)		+				+	
1983	Covello *et al.* (50)		+		+		+	
1983	NRC/Committee on the Institutional Means (51)	+			+	+		+
1983	Ricci *et al.* (52)	+	+	+	+	+	+	
1983	Rogers & Bates (53)	+	+	+	+			
1983	The Royal Society (54)	+	+	+	+			+
1983	Viscusi (55)			+	+	+	+	

dose–response, lifetime projection model, or both (79). For the poorly understood effects of weak carcinogens (e.g., saccharin) or for complex technologies (e.g., nuclear power plants), estimates may well vary by two or even three orders of magnitude. Nevertheless, insofar as a comparative perspective reveals the mortality risks of technological hazards to vary by six or more orders, even such imprecise estimates are useful in classifying or ranking hazards (80).

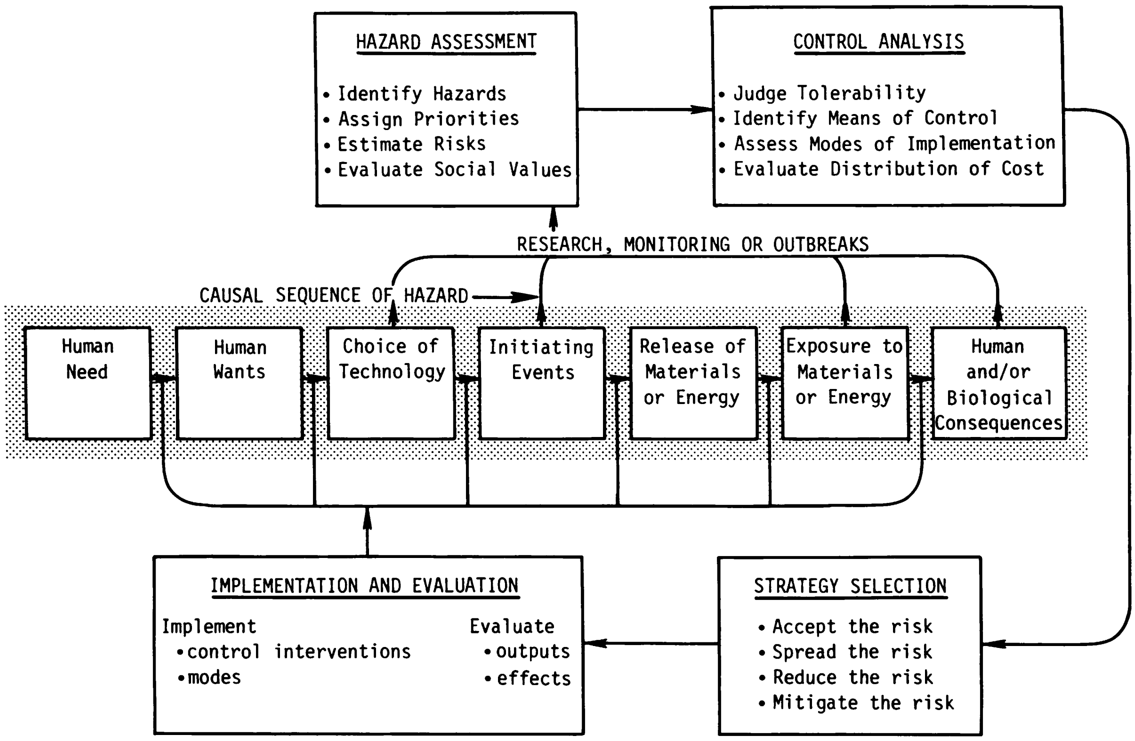

FIG. 1. **Flow chart of hazard management.**

Risk Acceptability or Tolerability. A key motivation for developing quantitative measures of risk is their use in answering the frequent, and somewhat misleading, question "how safe is safe enough?" The so-called "acceptable risk" issue has pervaded the literature from its inception when Starr (70), taking into account both benefits and the voluntary and involuntary nature of the imposition of risk, saw those risks "acceptable" to society "revealed" in the historic statistics of mortality. The stabilization of a level of risk over a period of time implies that society, through operation of the market, has accepted that degree of risk from a certain product or activity. Others have pointed out, however, that "accepted" is not the same as acceptable (81, 82), that "acceptability" connotes a degree of consent that rarely accompanies impositions of risk. In this sense, "tolerability" perhaps better captures most actual risk situations (83).

Whatever the label, more than 70% (in all, 39) of the books surveyed devote substantial attention to this issue. Most analyses proceed from an obvious assumption that all human activity is inherently hazardous to someone or something, that absolute safety is chimerical, that one must focus instead on determining the acceptable risk for a given activity.

That question reverberates at conferences and in the literature. One conference report centers directly on the question (25) whereas a second devotes a major section to the tolerability issue (42). A Rand Corporation study presents strategies for formulating risk-acceptance criteria (24). A slim, thoughtful monograph on risk acceptability summarizes the views of a working party of the Council for Science and Society in the United Kingdom (12). A major work, especially strong in its critique of methods and approaches, takes stock of the issue (41).

One finds virtual consensus that collective efforts allocated to managing a given hazard ought to be commensurate with the degree of threat—observed or perceived—posed by the technology or activity in question. Hence governmental agencies and interagency committees issue priority lists of carcinogens, toxic substances, and dangerous consumer products (84–86), and scientists propose classification schemes for ranking hazards and potential hazards (ref. 2, p. 14; refs. 80, 87, 88). Everyone agrees that there are hazards to be managed, that some hazards are more pressing than others, that society needs to focus on the important hazards. Disagreement surfaces with the inference that society should optimize (in an economic sense) its investment in risk reduction via some common metric (e.g., lives saved). Meanwhile, the approaches to dealing with these issues are a matter of style.

Some analysts take the optimistic tack of placing hazards in some comparative risk context. A recent paper (83) identified five such contexts: (*i*) natural background levels, (*ii*) other risks prevalent in society, (*iii*) magnitude of benefits, (*iv*) costs of control, and (*v*) risks and benefits of available alternatives. Comparisons with natural background levels (ref. 79, pp. 66–67) or with other hazards (89, 90) may encourage action (as in the case of radiation standards) or illuminate inconsistencies in tolerance for the same risks among different communities, cultures, and nations (26, 40, 91). Cost-effectiveness studies (5, 37, 92) seek to determine how much society is willing to spend to avoid particular consequences. Risk/benefit comparisons (39) allow for a balancing act to determine the degree of risk reduction that is in order. Cost/benefit approaches frequently entail putting a price on life and raise a myriad of thorny ethical issues (93, 94). A comparative examination of both the risks and the benefits of a potential substitute for an identified hazard (e.g., asbestos, flammable sleepwear) may affect efforts to ban or supplant a particular technology.

Significant methodological and ethical dilemmas plague most approaches, which in any event are misleading in the absence of quantitative estimates of risk. Moreover, mounting criticism of risk/benefit analysis and a widespread distaste for the putting-a-price-on-life aspects of cost/benefit analysis have provided the impetus for alternative methods.

Indeed, alternative approaches have proliferated. One approach seeks to simplify the problem of establishing a level of tolerable risk: designate certain hazards to be avoided at all costs (e.g., the Delaney Amendment requires the banning of all carcinogenic food additives) or tacitly label others as safe through the establishment of a *de minimis* level—an acceptable level of risk below which society should take no regulatory action whatsoever (95, 96). Another approach focuses on public process. The democratic process, buttressed by a wide spectrum of scientific information and policy considerations, allows for the participation of various interests in decision making. Some psychologists seek to inform the decision process by eliciting from the public its preferences for eliminating various risks (97–99). Another approach advocates direct participation by risk bearers in particular (5) or by the general public (46) in risk decisions through existing institutional processes. Still another approach stresses the role of information and the principles of informed consent (55, 100). A paper at one conference (83) stressed the role of equity analysis.

Finally, more pessimistic analysts, impressed by the uncertainty and complexity attendant on a specific hazard, find themselves overwhelmed by a seemingly relentless parade of new threats to health and safety (101, 102). Thus, in its early years, the CPSC favored an ad hoc, case-by-case approach, which has been labeled the quicksand of hazard management (103). The case-by-case approach has few advocates but numerous practitioners, however reluctant. Even those assessors who find themselves resorting to this method, however, seek a formula for improving the processes by which society makes judgments, expresses preferences, and arrives at decisions on risk.

Perception. Risk assessors have found all too often that their scientific findings diverge from popular perceptions of risk. Both scientific and popular assessments of risk constitute judgments, the former made with the assistance of formal and sometimes reproducible methodology, the latter derived via more informal and perhaps broader cognitive processes. A considerable research effort, which has progressed from the speculative to the scientific, has gone into identifying and understanding the nature of perceived risk.

Perhaps more than any other work, the pioneering research of Slovic, Fischhoff, and Lichtenstein—represented in virtually all collections of papers on risk—has enhanced the understanding of perceived risk. This trio of psychologists has elicited from various groups of experts and lay persons judgments of risk for some 90 technologies or activities. Other researchers have used similar techniques and produced consistent findings (99, 104). A principal finding of this work is that although ordinary people and experts display remarkable similarity in qualitative judgments of most risks, they differ in quantitative judgments, leading, for example, to serious over- or under-estimates of the mortality risk of specific hazards. Each group uses its own heuristics to cope with the complexity of making quantitative judgments. Variations in heuristics frequently account for discrepancies in such judgments (105).

Two strands of evidence may account for the quantitative discrepancies. First, a general tendency to overestimate the frequency of rare events and to underestimate the frequency of common events leads to a compression in the scale of probability judgments (98). Thus, for hazards with a risk span of six orders of magnitude, laypersons judge the difference between the highest and the lowest risks at two orders of magnitude, and even experts may estimate only four orders. Second, the discrepancy in judgments derives from the weighting of different dimensions of hazardousness. Whereas experts are prone to estimate risks almost entirely in terms of mortality, laypersons are more apt to consider other factors such as the catastrophic nature of the risk or the dread associated with its consequences.

The literature points to an increase in scholarly attention to public perception. Of the 54 volumes surveyed, 31 included substantial discussion of perceived risk. Moreover, 23 of these volumes appeared in the 1980s. One conference volume notes a mixture of speculation and empirical study (20). Two sets of data—the findings of Slovic and collaborators (97, 98) and the results of a study on the hazards of energy production in Austria (106, 107)—take up a large share of a Royal Society discussion (36). A more recent review by the Royal Society devotes an entire section to the perception of risk (54). It is noteworthy, too, that the first conference of the Society for Risk Analysis bore the title "The Analysis of Actual vs. Perceived Risks" (50).

Major broad-based surveys indicate that Americans believe that life is a risky proposition, that life is becoming riskier over time (63, 108). One recent poll (61) found three in four Americans agreeing that life in 1980 was riskier than 20 years before. Majorities of lenders, institutional investors, and members of Congress and pluralities of corporate executives and regulators shared this view. Ironically, overwhelming majorities of all groups also shared with the American public a belief that over the next 20 years the benefits of technology will outweigh the risks. This favorable attitude to technology is consistent with the results of numerous polls conducted since 1957 (63). A Harris survey in 1982 (62) established that Americans not only care about the environment but also are willing to pay for its protection. Moreover, an erosion of confidence in the public institutions charged with enforcing existing regulations has produced a heightened public perception of danger and a more vociferous demand for protection—all in the face of support for less federal regulation!

Analysis of Regulation. Although most risk decisions are made by individuals and many are made by corporations, the literature dwells on the relatively few that are made by government or at government insistence. The obvious bias is toward equating management with regulation. Discussions of experience with regulation or critiques thereof occur in more than half of the volumes surveyed.

The emphasis is on topics such as occupational health and safety (7, 55), risk/benefit analysis as a basis for regulatory action (39), participation of risk bearers in regulatory decisions (12), the role of scientific data (29, 47), and the consideration of benefits in health and safety regulations (30). One imaginative author proposes that regulatory agencies themselves concoct innovative alternatives to regulation—in the form of legal remedies, taxation, and other incentives (27). Espousing the return of decision-making power to the individual, all the contributors to another collection assume a radical stance and recommend an extreme alternative—true deregulation, or the abolition of major regulatory agencies (48).

Case Studies. Quite often discussions of regulation occur in the guise of case studies, which abound in the literature. More than half of the books surveyed use case studies in some frame of reference. The most ambitious use is Lawless's systematic comparison of 45 instances of technological shock (14). In providing for each case a comparable look at the timing and relationship of hazard identification, media coverage, and societal response, Lawless records the ways in which Americans have handled, or mishandled, a variety of hazards and implies that better methods are available. For the most part, the emphasis is on failures in managing technological hazards. In another forthcoming volume, a chapter title ("Tales of Woe") betrays a similar preoccupation with mismanagement in the 42 publications examined by the author (B. Johnson, personal communication).

Other volumes make less ambitious, yet significant, use of case studies. Crandall and Lave (29) enlist a scientist, an economist, and a regulator to confront the scientific bases for regulating passive restraints, cotton dust, waterborne carcinogens, saccharin, and sulfur dioxide. In another collection, studies on the management of carcinogenic risk in each of four countries—Norway, Sweden, Canada, and the United States—allow for cross-national comparisons (34). Another conference examined the handling of vinyl chloride from four different perspectives (18). A symposium volume includes case studies of Love Canal and Three Mile Island (42). A French author numbers cases such as the accident at Three Mile Island, the Seveso disaster, and the wreck of the *Amoco Cadiz* among the major technological risks of the century (46). Crouch and Wilson (39) prescribe a method for estimating risks for 10 comparable cases ranging from swine flu vaccination to nuclear power plant accidents. The first proceedings of the SRA includes studies of automobile accidents, smoking, and stratospheric ozone (50). A Canadian study used a series of case studies, ranging from toxic shock syndrome to the hazards of (2,4,5-trichlorophenoxy)-acetic acid (2,4,5-T), to illustrate concepts and methodologies and to describe and inform the management of environmental risks in Canada (38). In a study to be published elsewhere, we and a colleague have considered case studies of specific hazards [nuclear power, contraceptives, airborne mercury, polychlorinated biphenyls (PCBs), automobile accidents, and television] and hazard managers (the United States Congress and the CPSC) to test theory, validate a model of hazard structure, and inform the hazard-management process.

Such analytic use of case studies is rare. Lawless's systematic comparison of 45 cases (14), Lave's eight "decision frameworks" (33), and Crouch and Wilson's application to nine cases of their "prescription for useful analysis" (39) do much to advance conceptual understanding of hazard and risk. On the whole, however, few of the many and varied case studies at hand succeed in testing hypotheses about the nature of hazard and hazard management.

Research Agenda. A call for more and better case studies pervades much of the literature. Examination of those volumes that included research agenda—i.e., the equivalent of a chapter or more delineating specific directions or conceptual or methodological needs for future research—documents an acknowledgment that case studies invariably enhance the data base. Some volumes call for best-case analyses, for documentation of success stories in lieu of (or at least in addition to) bungled hazard management (13, 42). Others stress cross-national comparisons (2, 26). Some emphasize the need for comparative case studies of risk-management institutions (5, 45, 51), of the media (45), or of interest groups (8).

Case studies, then, assume a prominent niche on many research agenda. In the sense of affixing a "needs-more-work" label, virtually all the 54 volumes at least alluded to directions for future research. Yet only one-third of the volumes offered concrete proposals. Pedestrian platitudes aside, a number of issues seem to warrant further study. Some scientists expressed a discernible need for taxonomies or classification schemes for ordering and ranking hazards (13, 42, 53). Virtually all the agenda included some prescription for improving the quantitative data base, be it in aid of setting priorities, selecting among alternatives, or providing evidence of success or failure in managing a particular hazard. Others called for robust models of high quality (2), the development of prospective (rather than retrospective) animal model systems and a rational basis for extrapolation from animals to humans (34), and a need to refine methods for dealing with uncertainty (51). A number of agenda noted the need to conduct more studies of risk perception (25, 36, 54). Underlying all these agenda items is a respect for the contribution of science to hazard management.

Scientific contributions to hazard management

The identification, assessment, and management of technological hazards involve an extraordinary array of professional skill and disciplinary backgrounds (recall Table 1). Scientists occupy a unique niche, for the hazards associated with the production and use of technology often transcend the realm of ordinary experience and require expert study, assessment, and evaluation. Scientists bring to this task their understanding of basic physical, biological, and social principles as well as traditions for weighing evidence, handling uncertainty, and fostering international collaboration and communication.

This review suggests a few of the ways in which natural and social scientists can make a unique contribution or exercise a special responsibility.

Basic Science. The primary contribution is the practice of basic science. No advances in risk-assessment methodology or practice can contribute as much to assessing risk as would, for example, understanding the process of carcinogenesis; the interactions of biogeochemical cycles; or the relationship among threat, fear, and human behavior. In restating such an obvious task, it is worth sounding a cautionary note. Carcinogenesis, biogeochemical cycles, and human behavior are extraordinarily difficult subjects. Despite occasional claims of major progress (109, 110), fundamental understanding is still elusive. Within the time frame of requisite societal action in coping with hazard, such decisions will have to be made within the current bounds of uncertainty. Whereas improvement in basic scientific understanding remains the long-term goal of science, the short-run reality entails settling for ways of improving risk assessment and hazard management under conditions of considerable uncertainty and some basic ignorance.

Hazard Identification. In the main, the identification of hazards occurs through the monitoring of outbreaks (e.g., toxic shock syndrome, Tylenol poisonings) or by routine screening (e.g., the Ames test for mutagenic effects). Major advances have been made in the early detection of outbreaks and the routine use of monitoring networks and screening tests. In contrast to these "shotgun" methods of monitoring and screening, "sharpshooting" methods, using scientific theory, analog, and experimentation, serve to identify some hazards (e.g., chemical threats to stratospheric ozone).

The design and implementation of sensitive, low-cost, and acceptable monitoring and screening networks is a continuing scientific task, but it is an administrative and political one as well. Indeed, as successful monitoring networks become routine, they provide easy targets for budget-conscious administrations. The hospital emergency-room surveillance system of the Consumer Product Safety Commission, having experienced a recent cut in reporting hospitals from 119 to 74, is a case in point. Moreover, many of the resources for monitoring and screening are in the private sector. New social arrangements are needed to meld private and public resources under conditions of mutual trust. In this regard, the scientific community, with common interests that transcend employment, might play an exemplary leadership role.

Paced by advances in basic science, sharpshooting has moved beyond obvious concern with identifying hazards by their potential for the direct release of energy or toxic materials to a preoccupation with defining more subtle interactions. Surely this understanding of the subtleties of process, not only in chemicals but in all aspects of hazard initiation and management, marks the frontier for hazard identification. Attempts to control a hazard (e.g., flammability in children's sleepwear) may create a new one (Tris) or amplify exposure to an existing one (e.g., driver training in high school puts more high-risk drivers on the highways). Public identification of a hazard may lead to psychological distress exceeding that of all other health effects (e.g., the accident at Three Mile Island). Finally, new technologies (e.g., television) may lead to complex social changes, both beneficial and harmful, the magnitudes of which overshadow routine releases of hazardous energy or materials. To use the television example, control of radiation releases from color television sets took place early in the life of the technology. Generally, hundreds of studies have addressed information hazards such as the risks of televised violence (111). Yet today we know little about the effects of television on child development and learning behavior even though surveys report that the average American child spends more time before a television set than in school (112).

Risk Estimation. As noted, progress in scientific risk estimation depends fundamentally on progress in scientific understanding of principles of causality. Since many of the links in causal chains of hazard evolution are poorly understood, scientific risk estimation is essentially probabilistic and entails the handling of uncertainty. In this regard, science can inform hazard management in three important ways: establishing conventions, handling cumulative uncertainty, and presenting uncertainties to nonexperts.

Comparative risk analyses benefit from conventions in science. Such conventions (e.g., 1%, 5% levels of significance) ease the problems of standardization and familiarization in science even though they are inherently indefensible in absolute terms. Conventions in risk estimation would codify broad areas of scientific consensus that do exist and provide public reassurance about much that we do know and agree upon. From the perspective of comparative risk analysis, many sincerely held scientific differences tend to generate more heat than light. In the case of ionizing radiation, for example, widespread media attention to the recent report (79) of the Committee on the Biological Effects of Ionizing Radiation (BEIR III) of the NRC focused inordinately on controversy. The spotlighting of irreconcilable differences within the committee over the fit for the dose–response model (linear vs. quadratic vs. linear-quadratic) of low linear energy transfer, low-level radiation detracted from an important consensus. Within a factor of two to three, most scientists agree that the contribution of low-level radiation to cancer risk is relatively slight. Similarly, the debate about the precise way to extrapolate quantitatively from animal experiments to human carcinogenesis serves to obscure the basic consensus as to the relevance of animal experiments to human risk estimates. To the degree that science can forge a working consensus around certain conventions, or, in the words of a recent NRC committee, around "uniform inference guidelines" (51), the task of risk assessment will be considerably eased.

Most scientific disciplines harbor conventions or tacit understandings for handling uncertainty. The business of estimating risk, however, shows little respect for disciplinary boundaries. An attempt to estimate the potential increase in skin cancer and melanoma induced by ultraviolet radiation from ozone depletion by chlorofluorocarbon, may tap various methodologies of epidemiology; dose–response extrapolation; and chemical, atmospheric, and economic modeling (113–117). Such an analysis combines theoretical simulation models, laboratory reactions, clinical observations, epidemiological correlations, and expert judgments into a single estimate of risk. How best to estimate the cumulative uncertainty of the conclusion requires further scientific work and guidance from disciplines with comparable problems.

Even if it is possible to arrive at a scientific consensus as to the nature of the uncertainty that surrounds a risk estimate, equal care should accompany its public presentation. Extensive research on the heuristics and biases of judgment under uncertainty suggest that both experts and lay persons systematically distort probabilistic meaning (105). Risk-perception studies (cited above) confirm these observations. This research also renders it possible to describe better, if not best, procedures for publicly presenting risk estimates, although relatively few experiential studies address such methods (118, 119). The NRC Governing Board Committee on the Assessment of Risk lists the following practical suggestions:

1. Express numbers with their qualifiers and ranges of uncertainty. Do not use highly specific numbers in summaries or press releases if they need to be qualified in important ways. Only use them when they can be explained in context. They may be taken out of context but we should not inadvertently encourage doing so.
2. When significant uncertainty exists, as it almost always does in risk analyses, interval expression is preferable to point expression.
3. Avoid using evaluative descriptions of probabilities such as large, weak, significant, moderate, and such. Wherever possible, provide numerical estimates with the appropriate caveats concerning their quality; in particular, estimates of ranges of uncertainty should be provided.
4. Because untrained individuals have difficulty in appreciating numbers such as 10^{-8}, judicious use should be made of comparisons with familiar events of the same magnitude. Care must be exercised not to seem to trivialize the risk nor to mislead about the uncertainty of the estimate (75).

Another committee cautions scientists to beware of numbers. Quantitative estimates may impart a false sense of precision and imply that more is known than is actually known; the absence of numbers may convey a false sense of imprecision and suggest that less is known than is actually known (2).

Risk Evaluation. Science can contribute to the discussion of what constitutes tolerable risk but cannot make the decision either for individuals or for society. This is in contrast to its key role in the estimation of risks. Indeed, a recurrent theme in the literature is the attempt to distinguish between scientific questions of assessment and value judgments of policy (120, 121).

The division is not as clear as it may seem. Risk estimation is not in itself a value-free activity. An assessor's economic, social, political, or moral views and the context of the assessor's employment influence, often in subtle ways, the choice of risks to be assessed and the methodologies to be employed (122). Nonetheless, standards and conventions of scientific evidence, discourse, and review provide a forum for estimating risks primarily as questions of science.

Scientists can contribute to risk evaluation in at least three ways: (*i*) by setting risk estimates into comparative contexts, (*ii*) by scientific study of the process of evaluation, and (*iii*) by participating in societal judgments as knowledgeable individuals. As noted above, scientists can provide contextual information necessary to compare risks (83). Quantitative data on natural background levels, on other risks, on benefits, on the costs of hazard management and control, and on the pros and cons of alternative technologies aid the comparison process. Moreover, such comparative data should eventually generate a systematics of hazards. Taxonomies, such as the seven-class scheme in Table 4, can assist society in its evaluative ordering of hazards.

Scientists can heed the numerous calls for taxonomies (13, 80, 83, 87, 88) by developing new ones and improving or refining existing ones. Such schemes allow for a systematic ranking of hazards that will facilitate the setting of priorities, establish some rationale for decision making, and promote the

Table 4. A seven-class taxonomy*

Class	Examples
Multiple extreme hazards	Nuclear war (radiation), recombinant DNA, pesticides
Extreme hazards	
Intentional biocides	Chain saws, antibiotics, vaccines
Persistent teratogens	Uranium mining, rubber manufacture
Rare catastrophes	Liquefied natural gas explosions, commercial aviation (crashes)
Common killers	Automobile crashes, coal mining (black lung)
Diffuse global threats	Fossil fuel (CO_2 release), supersonic transport (ozone depletion)
Hazards	Saccharin, aspirin, appliances, skateboards, bicycles

*Taken from ref. 80, p. 382.

grouping of similar hazards for more efficient management.

Scientists can also assist in the process by observing how individuals and societies actually go about making such evaluations of risk. They can then assess in the light of such findings the variant strengths and weaknesses of the alternative normative procedures (comparative risk catalogues, cost/benefit analysis, decision analysis) for making evaluations. Finally, knowledgeable individual scientists or groups have a right and perhaps a duty to issue value judgments on risks and to prescribe remedial action. Value judgments should be labeled as such, however, and they should be separated from judgments of scientific evidence that are subject to demonstration, replication, and verification (51).

Hazard Management. The management of hazard is one of those important human undertakings that cuts across traditional ways of classifying activity. In economic terms, for example, the burden of hazard in the United States is equivalent to the gross national product (GNP) from agriculture, forestry, fishing, and mining combined, but that does not show in any of the GNP statistics. Thus, as with other crosscutting activities (e.g., research and development), hazard management as an activity deserves and receives significant social science study. Beyond such study, scientists can contribute to the task itself in at least two important ways: by broadening our understanding of the range of possible actions and by providing improved tools for evaluation of success.

In hazard management, we can distinguish between *control actions* that seek to block the evolution of the causal chain of hazard and the *modes of implementation* used to induce adoption of those actions. In general, hazard management employs relatively few of the available control actions, although the number is expanding over time. In the control of accidental releases of radiation from nuclear power plants, for example, the bulk of regulations up to 1975 were designed to prevent such accidental releases and almost none to mitigate their effects after they occurred. Following Three Mile Island, emergency sheltering and evacuation procedures have become a major focus of the Nuclear Regulatory Commission.

Similarly, the range of implementation modes in the United States seems excessively constrained, with inordinate attention devoted to regulation. Using systematic tools of analysis, science can identify new or underutilized opportunities for hazard reduction and control and methods of implementation (recall Fig. 1). Through comparative studies of hazard management in industrialized countries we can expand our knowledge of alternative modes. Indeed, basic social experiments are being conducted through the diversity of national or provincial policies and styles. In areas as different as occupational health, mandating seat-belt use, or use of nuclear power, fundamentally different policies and modes of implementation can be found.

Threshold limit values (TLVs) for workplace ambient air standards are stricter in Eastern Europe and the U.S.S.R. than in the United States and Western Europe by factors of 10–20 (91, 123), although little is known about actual enforcement of official standards. Occupational health responsibility is primarily regulated in the United States (7, 124), is much bargained for in the United Kingdom (125), and is shared by labor and government in Sweden (124, 126). Twenty-eight countries as diverse as Australia, France, Malaysia, Japan, and Greece have mandatory seat-belt laws—a practice that is viewed, surprisingly, given a strong regulatory bent, as "out of the question" for the United States (127). Nuclear power policies range from total bans in Austria, Denmark, and Norway, to *de jure* moratoria in Sweden, to *de facto* moratoria such as in the United States, to strongly enthusiastic as in France, Japan, and the U.S.S.R. Observing such differences and synthesizing findings are salutary scientific contributions to a more inclusive hazard management.

A fascinating question raised by this diversity is whether it makes a difference. Does convergence at the level of science, technology, and multinational industry take place to such an extent that hazard management differences are of style rather than risk? Vital statistics offer a clue—more than 8 in 10 Swedes live to age 65, but in the United States, which ranks 26th in this measure of life extension, it is 7 in 10 who survive. And for Black Americans, fewer than 6 in 10—about the same as Mexico—survive to age 65 (2, pp. 4–5). The meaning of these differences is open to speculation with regard to size effects, homogeneity of population, consensual commitment to welfare and equity, or maturation of the hazard-management system (2). Other clues emerge in cross-national studies of hazard management. A recent comparison of national policies for regulating toxic chemicals found that fundamental differences in decision-making style and procedure in four countries (the United States, England, France, and the Federal Republic of Germany) produced no significant differences in choice of regulatory targets or control standards (128).

But more precise answers to such global questions and to more specific ones over choice of control actions and modes of implementation await better measures of evaluation of managerial success. Two widely used comparative measures are deaths per unit of exposure and costs per incremental life saved but even these are at best crude estimates. Other important measures such as reduction of catastrophic mortality, decrease in long-term morbidity, reduced benefits, provision of equity, or public acceptance, or reduced public concern receive short shrift in the literature. Devising a set of meaningful evaluative measures of success in hazard management is an important scientific task. Increasingly within industry and the public sector there is a desire for social and environmental audits in which hazard management plays a significant role, but the methodologies for such audits are still not well-developed.

Epilogue

In the first half of the 19th century, the hazard managers of New York City faced mortality patterns somewhat comparable with those of certain developing countries today: death due primarily to infectious diseases and infant mortality. Beginning prior to the germ theory of disease, they undertook to improve the public health in fits and starts that lasted 50 years and reduced by two-thirds the mortality within the city (J. Tuller, personal communication). If in the middle of this effort they paused to take stock they may have appeared to themselves somewhat as we do to ourselves today in coping with the major causes of death in industrialized nations—still debating the occupational fraction of cancer, unable to explain surprising declines in mortality (such as stomach cancer or more recently cardiovascular disease), and wondering whether socially or individually we are doing too much or too little in pursuit of a less risky environment. In the midst of that great demographic transition, comparative risk analysts might have displayed as much excitement, sense of mission, and confusion as they do today, albeit with fewer publications to their credit. But looking backward, we find splendid achievement and a hazard-management system, now codified and conventional, replete with vaccinations, building codes, and protected water supplies.

We have benefited immensely from the insights of colleagues Christoph Hohenemser and Roger E. Kasperson and members of the NRC Governing Board Committee on the Assessment of Risk. Also, we thank Jesse Ausubel, Duncan Luce, Paul Slovic, Chris Whipple, and Gilbert F. White for their constructive comments and Daniel Koshland for his patient encouragement.

1. Brooks, H. (1973) *Zygon* **8**, 17–35.
2. National Research Council, Committee on Risk and Decision Making (1982) *Risk and Decision Making: Perspectives and Research* (National Academy Press, Washington, DC).
3. Calabresi, G. (1970) *The Costs of Accidents* (Yale Univ. Press, New Haven, CT).
4. National Academy of Engineering, Committee on Public Engineering Policy (1972) *Perspectives on Benefit-Risk Decision Making* (NAE, Washington, DC).
5. Sinclair, C., Marstrand, P. & Newick, P. (1972) *Innovation and Human Risk: The Evaluation of Human Life and Safety in Relation to Technical Change* (Centre for the Study of Industrial Innovation, London).
6. Epstein, S. S. & Grundy, R. D., eds. (1974) *The Legislation of Product Safety* (MIT Press, Cambridge, MA), 2 vols.
7. Ashford, N. A. (1975) *Crisis in the Workplace: Occupational Disease and Injury* (MIT Press, Cambridge, MA).
8. Chicken, J. C. (1975) *Hazard Control Policy in Britain* (Pergamon, New York).
9. National Research Council, Committee for the Working Conference on Principles of Protocols for Evaluating Chemicals in the Environment and Committee on Toxicology (1975) *Principles for Evaluating Chemicals in the Environment* (National Academy of Sciences, Washington, DC).
10. National Research Council, Committee on Principles of Decision Making for Regulating Chemicals in the Environment (1975) *Decision Making for Regulating Chemicals in the Environment* (National Academy of Sciences, Washington, DC).
11. Lowrance, W. W. (1976) *Of Acceptable Risk: Science and the Determination of Safety* (William Kaufmann, Los Altos, CA).
12. Council for Science and Society (1977) *The Acceptability of Risks* (Barry Rose, London).
13. Kates, R. W., ed. (1977) *Managing Technological Hazard: Research Needs and Opportunities*, Program on Technology, Environment and Man, Monograph 25 (Institute of Behavioral Science, Univ. of Colorado, Boulder).
14. Lawless, E. W. (1977) *Technology and Social Shock* (Rutgers Univ. Press, New Brunswick, NJ).
15. Rowe, W. D. (1977) *An Anatomy of Risk* (Wiley, New York).
16. Kates, R. W. (1978) *Risk Assessment of Environmental Hazard*, Scientific Committee on Problems of the Environment, SCOPE 8 (Wiley, New York).
17. Goodman, G. T. & Rowe, W. D., eds. (1979) *Energy Risk Management* (Academic, New York).
18. Hammond, E. C. & Selikoff, I. J., eds. (1979) *Ann. N.Y. Acad. Sci.* **329**.
19. Conrad, J., ed. (1980) *Society, Technology and Risk Assessment* (Academic, New York).
20. Dierkes, M., Edwards, S. & Coppock, R., eds. (1980) *Technological Risk: Its Perception and Handling in the European Community* (Oelgeschlager, Gunn and Hain, Cambridge, MA).
21. Dowie, J. & Lefrere, P., eds. (1980) *Risk and Chance: Selected Readings* (Open Univ. Press, Milton Keynes, United Kingdom).
22. Hovden, J. (1980) *Accident Risks in Norway: How Do We Perceive and Handle Risks?* (Risk Research Committee, Royal Norwegian Council for Scientific and Industrial Research, Oslo).
23. The Open University (1980) *Risk: A Second-Level University Course* (Open Univ. Press, Milton Keynes, United Kingdom), 6 vols.
24. Salem, S. L., Solomon, K. A. & Yesley, M. S. (1980) *Issues and Problems in Inferring a Level of Acceptable Risk* (R-2561-DOE; Rand Corporation, Santa Monica, CA).
25. Schwing, R. C. & Albers, W. A., eds. (1980) *Societal Risk Assessment: How Safe Is Safe Enough?* (Plenum, New York).
26. Whyte, A. V. & Burton, I., eds. (1980) *Environmental Risk Assessment*, Scientific Committee on Problems of the Environment, SCOPE 15 (Wiley, New York).
27. Baram, M. S. (1981) *Alternatives to Regulation: Managing Risks to Health, Safety and the Environment* (Lexington Books, Lexington, MA).
28. Berg, G. C. & Maillie, H. D., eds. (1981) *Measurement of Risks* (Plenum, New York).
29. Crandall, R. W. & Lave, L. B., eds. (1981) *The Scientific Basis of Health and Safety Regulation* (Brookings Institution, Washington, DC).
30. Ferguson, A. R. & LeVeen, E. P., eds. (1981) *The Benefits of Health and Safety Regulation* (Ballinger, Cambridge, MA).
31. Griffiths, R. F., ed. (1981) *Dealing with Risk* (Wiley, New York).
32. Haimes, Y. Y., ed. (1981) *Risk/Benefit Analysis in Water Resources Planning and Management* (Plenum, New York).
33. Lave, L. B. (1981) *The Strategy of Social Regulation* (Brookings Institution, Washington, DC).
34. Nicholson, W. J., ed. (1981) *Ann. N.Y. Acad. Sci.* **363**.
35. Richmond, C. R., Walsh, P. J. & Copenhaver, E. D., eds. (1981) *Health Risk Analysis* (Franklin Institute Press, Philadelphia).
36. The Royal Society, Study Group on Risk (1981) *The Assessment and Perception of Risk: A Royal Society Discussion* (Royal Society, London).
37. Siddall, E. (1981) *Risk, Fear and Public Safety*, Report AECL-7404 (Atomic Energy of Canada Limited, Mississauga, ON).
38. Burton, I., Fowle, C. D. & McCullough, R. S. (1982) *Living with Risk: Environmental Risk Management in Canada* (Institute of Environmental Studies, Univ. of Toronto, Toronto).
39. Crouch, E. A. C. & Wilson, K. (1982) *Risk/Benefit Analysis* (Ballinger, Cambridge, MA).
40. Douglas, M. & Wildavsky, A. (1982) *Risk and Culture: An Essay on the Selection of Technical and Environmental Dangers* (Univ. of Calif. Press, Berkeley, CA).
41. Fischhoff, B., Lichtenstein, S., Slovic, P., Derby, S. & Keeney, R. L. (1982) *Acceptable Risk* (Cambridge Univ. Press, New York).
42. Hohenemser, C. & Kasperson, J. X., eds. (1982) *Risk in the Technological Society*, American Association for the Advancement of Science Selected Symposium no. 65 (Westview, Boulder, CO).
43. Inhaber, H. (1982) *Energy Risk Assessment* (Gordon & Breach, New York).
44. Kunreuther, H. C., ed. (1982) *Risk: A Seminar Series* (International Institute for Applied Systems Analysis, Laxenburg, Austria).
45. Kunreuther, H. C. & Ley, E. V., eds. (1982) *The Risk Analysis Controversy: An Institutional Perspective* (Springer, New York).
46. Lagadec, P. (1982) *Major Technological Risk: An Assessment of Industrial Disasters* (Pergamon, New York).
47. Lave, L. B., ed. (1982) *Quantitative Risk Assessment in Regulation* (Brookings Institution, Washington, DC).
48. Poole, R. W., ed. (1982) *Instead of Regulation: Alternatives to Federal Regulatory Agencies* (Lexington Books, Lexington, MA).
49. Prentice, R. L. & Whittemore, A. S., eds. (1982) *Environmental Epidemiology: Risk Assessment* (SIAM, Philadelphia).
50. Covello, V. T., Flamm, W. G., Rodricks, J. & Tardiff, R., eds. (1983) *The Analysis of Actual vs. Perceived Risk* (Plenum, New York).
51. National Research Council, Committee on the Institutional Means for Assessment of Risks to Public Health (1983) *Risk Assessment*

in the Federal Government: Managing the Process (National Academy Press, Washington, DC).
52. Ricci, P., Sagan, L. & Whipple, C., eds. (1983) *Technological Risk Assessment* (Sijthoff & Noordhoff, Alphen aan den Rijn, The Netherlands).
53. Rogers, J. T. & Bates, D. V., eds. (1983) *Risk: A Symposium on the Assessment and Perception of Risk to Human Health in Canada* (Royal Society of Canada, Ottawa).
54. The Royal Society, Study Group on Risk (1983) *Risk Assessment: A Study Group Report* (The Royal Society, London).
55. Viscusi, W. K. (1983) *Risk by Choice* (Harvard Univ. Press, Cambridge, MA).
56. Agricola, G. (1556) *De re metallica* Translated: Hoover, H. C. & Hoover, L. C. (1950) (Dover, New York).
57. Commoner, B. (1971) *The Closing Circle* (Knopf, New York).
58. U.S. Food and Drug Administration (1979) *Fed. Regist.* **55,** 17076.
59. Calabrese, E. J. (1983) *Principles of Animal Extrapolation* (Wiley, New York).
60. Mitchell, R. C. (1980) *Public Opinion on Environmental Issues: Results of a National Opinion Survey* (Council on Environmental Quality, Washington, DC).
61. Marsh and McLennan Companies (1980) *Risk in a Complex Society: A Marsh and McLennan Public Opinion Survey*, conducted by Louis Harris and Associates (Marsh and McLennan, New York).
62. Harris, L. (1983) *Hearings on American Attitudes Toward Clean Water Before the Senate Committee on Environment and Public Works*, 97th Cong., 2nd Sess., Serial 97-H68 (December 15, 1982) (statement of L. Harris).
63. *Science Indicators 1980* (1981) (National Science Board, National Science Foundation, Washington, DC), pp. 158–179.
64. Greenwood, D. R., Kingsbury, G. L. & Cleland, J. G. (1979) *Handbook of Key Federal Regulations for Multimedia Environmental Control*, EPA-600/7-79-175 (Environmental Protection Agency, Washington, DC).
65. Industrial Union Dept., AFL-CIO v. American Petroleum Institute *et al.*, 78-911 (U.S. Court of Appeals, 5th Cir., July 2, 1980).
66. People Against Nuclear Energy v. Nuclear Regulatory Commission, 81-1131. (U.S. Court of Appeals, DC Cir., May 14, 1982).
67. Insurance Institute for Highway Safety (1982) *Highway Loss Reduction Status Rept.* **17** (11), 1–2.
68. Bazelon, D. L. (1979) *Science* **205,** 277–280.
69. Markey, H. (1980) *Chem. Eng. News* **58** (47), 5.
70. Starr, C. (1969) *Science* **165,** 1232–1238.
71. Otway, H. (1980) in *Society, Technology and Risk Assessment*, ed. Conrad, J. (Academic, New York), pp. 163–164.
72. Burton, I., Kates, R. W. & White, G. F. (1978) *The Environment as Hazard* (Cambridge Univ. Press, New York).
73. Covello, V. T. & Abernathy, M. (1983) in *Technological Risk Assessment*, eds. Ricci, P., Sagan, L. & Whipple, C. (Sijthoff & Noordhoff, Alphen aan den Rijn, The Netherlands).
74. Okrent, D., ed. (1975) *Risk-Benefit Methodology and Applications: Some Papers Presented at the Engineering Foundation Workshop, Sept. 22–26 1975*, UCLA-ENG-7598 (Univ. of California, Los Angeles).
75. National Research Council, Governing Board Committee on the Assessment of Risk (1981) *The Handling of Risk Assessments in National Research Council Reports* (Governing Board, National Research Council, National Academy of Sciences, Washington, DC).
76. Kasperson, R. E. & Morrison, M. (1982) in *Risk in the Technological Society*, eds. Hohenemser, C. & Kasperson, J. X. (Westview, Boulder, CO), pp. 303–331.
77. Covello, V. T. & Menkes, J. (1982) in *Risk in the Technological Society*, eds. Hohenemser, C. & Kasperson, J. X. (Westview, Boulder, CO), pp. 287–301.
78. Motor Vehicle Manufacturers Association (1982) *MVMA Motor Vehicle Facts and Figures '82* (MVMA, Detroit, MI).
79. National Research Council, Committee on the Biological Effects of Ionizing Radiation (1980) *The Effects on Populations of Exposure to Low Levels of Ionizing Radiation: 1980* (National Academy Press, Washington, DC).
80. Hohenemser, C., Kates, R. W. & Slovic, P. (1983) *Science* **220,** 378–384.
81. O'Riordan, T. (1977) *Environ. Planning* **9,** 3–14.
82. Jones, D. R. & Akehurst, R. L. (1980) *Bull. Inst. Math. Appl.* **16,** 252–258.
83. Kasperson, R. E. & Kasperson, J. X. (1983) in *Risk: A Symposium on the Assessment and Perception of Risk to Human Health in Canada*, eds. Rogers, J. T. & Bates, D. V. (Royal Society of Canada, Ottawa), pp. 135–155.
84. Interagency Regulatory Liaison Group, Work Group on Risk Assessment (1979) *Fed. Regist.* **44,** 39858–39879.
85. Toxic Substances Strategy Committee (1979) *Toxic Chemicals and Public Protection* (TSSC, Washington, DC), pp. 136–145.
86. U.S. Environmental Protection Agency, Office of Toxic Substances (1977, 1978) *Candidate List of Chemical Substances* (1977), Vols. 1–3; *Addenda 1 and 2* (1978).
87. Gori, G. B. (1980) *Science* **208,** 256–261.
88. Litai, D., Lanning, D. D. & Rasmussen, N. C. (1983) in *The Analysis of Actual vs. Perceived Risks*, eds. Covello, V., Flamm, W. G., Rodricks, J. & Tardiff, R. (Plenum, New York), pp. 213–233.
89. Cohen, B. & Lee, I.-S. (1979) *Health Phys.* **36,** 707–722.
90. Wilson, R. (1979) *Technol. Rev.* **81,** 41–46.
91. Derr, P., Goble, R., Kasperson, R. E. & Kates, R. W. (1981) *Environment* **23** (7), 6–15, 31–36.
92. U.S. Department of Transportation (1976) *The National Highway Safety Needs Report* (DOT, Washington, DC).
93. Kelman, S. (1980) *Regulation* **5** (1), 33–40.
94. Hapgood, F. (1979) *Atlantic Monthly* **243** (1), 33–38.
95. Comar, C. I. (1979) *Science* **203,** 319.
96. Eisenbud, M. (1980) in *Quantitative Risk in Standard Setting*, Proceedings of the Sixteenth Annual Meeting of the National Council on Radiation Protection and Measurements (NCRP, Washington, DC), pp. 64–72.
97. Fischhoff, B., Slovic, P., Lichtenstein, S., Read, S. & Combs, B. (1978) *Policy Sci.* **8,** 127–152.
98. Slovic, P., Fischhoff, B. & Lichtenstein, S. (1979) *Environment* **21** (3), 14–20, 36–39.
99. Vlek, C. A. & Stallen, P. J. M. (1981) *Organ. Behav. Hum. Perform.* **28,** 235–271.
100. MacLean, D. E. (1983) *Risk Anal.* **2** (2), 59–67.
101. Turner, J. S. (1976) *The Chemical Feast* (Penguin, New York).
102. Shapo, M. (1979) *A Nation of Guinea Pigs: The Unknown Risks of Chemical Technology* (Free Press, New York).
103. Bick, T. & Kasperson, R. E. (1979) *Environment* **21,** 7–15, 29–38.
104. Lee, T. R. (1981) *Proc. R. Soc. London Ser. A* **376,** 5–16.
105. Kahneman, D., Slovic, P. & Tversky, A. (1982) *Judgment Under Uncertainty: Heuristics and Biases* (Cambridge Univ. Press, New York).
106. Otway, H. J. & Fishbein, M. (1976) *The Determinants of Attitude Formation: An Application to Nuclear Power*, RR-80-15 (International Institute for Applied Systems Analysis, Laxenburg, Austria).
107. Thomas, K., Swaton, E., Fishbein, M. & Otway, H. J. (1980) *Behav. Sci.* **25,** 332–334.
108. Laporte, T. R. & Metlay, D. (1975) *Science* **188,** 121–127.
109. Frei, E. (1982) *Science* **217,** 600–605.
110. American Cancer Society (1983) *Cancer Facts and Figures 1983* (American Cancer Society, New York).
111. National Institute of Mental Health (1982) *Television and Behavior: Ten Years of Scientific Progress and Implications for the Eighties*, ADM 82-1195 (U.S. Dept. of Health and Human Services, Rockville, MD), Vol. 1.
112. Nielsen, A. C. (1981) *Nielsen Report on Television 1981* (A. C. Nielsen Co., Northbrook, IL).
113. National Research Council, Climatic Impact Committee (1975) *Environmental Impact of Stratospheric Flight: Biological and Climatic Effects of Aircraft Emissions in the Stratosphere* (National Academy of Sciences, Washington, DC).
114. National Research Council, Committee on Impacts of Stratospheric Change (1976) *Halocarbons: Environmental Effects of Chlorofluoromethane Release* (National Academy of Sciences, Washington, DC).
115. National Research Council, Committee on Impacts of Stratospheric Change (1976) *Halocarbons: Effects on Stratospheric Ozone* (National Academy of Sciences, Washington, DC).
116. National Research Council, Committee on Impacts of Stratospheric Change (1979) *Protection Against Depletion of Stratospheric Ozone by Chlorofluorocarbons* (National Academy of Sciences, Washington, DC).

117. National Research Council, Committee on Impacts of Stratospheric Change (1979) *Stratospheric Ozone Depletion by Halocarbons: Chemistry and Transport* (National Academy of Sciences, Washington, DC).
118. Slovic, P., Fischhoff, B. & Lichtenstein, S. (1980) in *Product Labeling and Health Risks*, Banbury Report 6, eds. Morris, L., Mazis, M. & Barofsky, B. (Cold Spring Harbor Laboratory, Cold Spring Harbor, NY).
119. Slovic, P., Fischhoff, B. & Lichtenstein, S. (1981) *Health Phys.* **41**, 589–598.
120. Hammond, K. R. & Adelman, L. (1976) *Science* **194**, 389–396.
121. Fischhoff, B. (1979) in *Energy Risk Management*, eds. Goodman, G. & Rowe, W. D. (Academic, New York).
122. Martin, B. (1979) *The Bias of Science* (Society for Social Responsibility in Science, Canberra, Australia).
123. International Labour Office (1977) *Occupational Exposure Limits for Airborne Toxic Substances* (ILO, Geneva).
124. Kelman, S. (1981) *Regulating America, Regulating Sweden: A Comparative Study of Occupational Safety and Health Policy* (MIT Press, Cambridge, MA).
125. Great Britain, Committee on Safety and Health at Work ([1972] 1975) *Safety and Health at Work* (Her Majesty's Stationery Office, London).
126. Kasperson, R. E. (1983) *Environment* **25** (4), 13–20, 40–43.
127. Claybrook, J., Gillan, J. & Strainchamps, A. (1982) *Reagan on the Road: The Crash of the U.S. Auto Safety Program* (Public Citizen, Washington, DC).
128. Brickman, R., Jasanoff, S. & Ilgen, T. (1982) *Chemical Regulation and Cancer: A Cross-National Study of Policy and Politics* (National Technical Information Service, Springfield, VA).